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TRANSLATIONS ON USSR SCIENCE AND TECHNOLOGY
PHYSICAL SCIENCES AND TECHNOLOGY
(FOUO 34/79)

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TRANSLATIONS ON USSR SCIENCE AND TECHNOLOGY

PHYSICAL SCIENCES AND TECHNOLOGY

(FOUO 34/79)

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CYBERNETICS, COMPUTERS AND AUTOMATION TECHNOLOGY

ABSTRACTS FROM THE JOURNAL 'PROGRAMMING', SEP-OCT 78

Moscow PROGRAMMIROVANIYE in Russian No 5, Sep-Oct 78 pp 95-96

UDC 681.3.06

COMPOSITION OF PROGRAMS AND COMPOSITIONAL PROGRAMMING

[Abstract of article by Red'ko, V.N.]

[Text] Mathematical models adequately reflecting methods of presentation of complex programs via simple ones are described. A complete overview of these models is given in terms of compositions. Consequently the chief classes of composition are specified: connotative and denotative. A method of compositional programming is developed on their basis.

UDC 681.142

ON FORMALIZATION OF LANGUAGE

[Abstract of article by Tuzov, V.A.]

[Text] The problem of precise description of a language with the aid of two grammars which generate external and internal languages is considered. General questions arising from this method of description are discussed. The problem of correspondence between these languages is solved.

UDC 681.322.06

ON THE TECHNOLOGY OF CREATION OF TRANSLATORS

[Abstract of article by Kaufman, V. Sh.]

[Text] The problem of rationalization of the process of translator creation is considered. It is proposed to specify it in two stages: elaboration of a projection from input language into output and realization of the projection by specific algorithms. This description is considered as assignment for translator in automated systematic programming of translators system.

UDC 681.3.323

PROBLEM OF CORRECTNESS OF GRAPH FLOWCHARTS OF PARALLEL ALGORITHMS

[Abstract of article by Korablin, Yu. P.]

[Text] Formal conditions of correctness of graph flowcharts of parallel algorithms are introduced in the article. These are adequate conditions of meaningful correctness (functionality) of graph flowcharts of parallel algorithms. The solvability of the problem of correctness of graph flowcharts of parallel algorithms is proven and a method of determining correctness for them is cited.

UDC 681.3.323

ON THE PROBLEM OF DEPARALLELIZATION OF ALGORITHMS

[Abstract of article by Belousov, A.I.]

[Text] An attempt is made to study certain aspects of the process of deparallelization of algorithms based on the theory of normal algorithms. The task of deparallelization is treated as a problem of expansion of normal algorithms into a parallel composition (association). Basic principles of this approach to the problem are formulated and certain conditions of expansion are derived.

UDC 681.31:681.326:681.142

ALGORITHMS OF OPERATIVE PLANNING OF WORK OF A DISTRIBUTED COMPUTING SYSTEM IN INTERACTIVE COMPUTATION MODE

[Abstract of article by Gavrilov, A.V. and Zhiratkov, V.I.]

[Text] The problem of control of a distributed computing system (RVS) functioning in interactive computing mode is considered. Features of solution of this problem for RVC are considered; a series of heuristic algorithms of planning are proposed; a study is made of the characteristics of the proposed algorithm; and practical recommendations are made for their use.

UDC 681.3

PROGRESSIVE-CATENARY ORGANIZATION OF OVERFLOW ENTRIES IN RANDOMIZED FILES

[Abstract of article by Litvinov, V.A. and Kokorin, A.A.]

[Text] Algorithms for processing synonyms in randomized files are considered which combine the basic merits of methods of progressive overflow and catenary connections. Results of statistical simulation are given.

UDC 519.95

KIMDS--COMPLEX OF PROCEDURES OF IMITATIVE SIMULATION OF GENERALIZED DISCRETE SYSTEMS

[Abstract of article by Mitrofanov, Yu.I. and Ivanov, A.N.]

[Text] Principles of construction of KIMDS complex of procedures of imitative simulation of generalized discrete systems using Algol-60 are examined. Complex KIMDS expands Algol-60 into a language of time simulation of discrete systems with processes evolving along parallel time lines.

UDC 681.3.06

ONE ALGORITHM OF TABULAR ORGANIZATION USING HASHING

[Abstract of article by Akchurin, R.M.]

[Text] Methods are given for organizing tables, the shortcomings of current methods, and an algorithm is proposed for tabular hashing of identifiers to permit significant reduction of retrieval time. Methods presented are of practical use for hashing based on author's standard module employing assembly language.

UDC 681.3.06:51

NEATPL--MEANS OF FACILITATING DEBUGGING OF PROGRAMS IN PL/1

[Abstract of article by Bezrukov, N.N.]

[Text] Article describes service program designed for structural opening of program text in PL/1 and other actions (automatic replacmeent of identifiers, list printing process control, translation of diagnostic messages of compiler, etc.), facilitating process of program debugging.

UDC 658.021.011.56:681.3.06

MODULE OF TEXTUAL INFORMATION PLACEMENT

[Abstract of article by Khannanov, R.G.]

[Text] Article reports on family of programming modules for placement of textual information in graphs of required dimensions, observing rules of grammatical transfer.

8617
CSO: 1870

CYBERNETICS, COMPUTERS AND AUTOMATION TECHNOLOGY

ABSTRACTS FROM THE JOURNAL 'PROGRAMMING', NOV-DEC 78

Moscow PROGRAMMIROVANIYE in Russian No 6, Nov-Dec 78 pp 95-96

UDC 681.142.2

[Text]

Methods of Defining the Semantics of Programming Languages.
Lavrov S.S., PROGRAMMIROVANIYE, 1978, No 6.

A brief survey of the semantics of programming languages is given. Primary attention is devoted to denotative (mathematical) semantics, which is essentially the theory of program models, built on the basis of set theory. The basic concepts and results of denotative semantics are presented. Some 23 bibliographic citations.

UDC 61:681.3.06

Logic and Termwise Equivalent Transformations of Yanov Schemes
Sin L.I., PROGRAMMIROVANIYE, 1978, No 6.

Yanov schemes are studied in this paper in terms of the informational influence of operators on the logic variables and operators, as well as their equivalence. A complete system of logic and termwise equivalent transformations of several subclasses of schemes is constructed, which contain structured (iterative) Yanov schemes. Some 8 figures, 7 bibliographic citations.

UDC 681.142.2

Automatic Machines which Recognize Languages Generated by Precedence Grammars
Babichev A.V., PROGRAMMIROVANIYE, 1978, No 6.

Precedence relationships for contextual grammars are defined in a new way. A class of machines is ascertained which identify languages generated by precedence grammars. Some 3 bibliographic citations.

UDC 681.3.06

A Method of Constructing Commutative Mappings of Data Models when Integrating Inhomogeneous Data Bases
Kalinichenko L.A., PROGRAMMIROVANIYE, 1978, No 6.

The problems of transforming data models in systems for integrating inhomogeneous data bases are considered. A general method is proposed for mapping one data model into another, based on an axiomatic expansion of the target data model, which provides for commutativity of the mapping diagrams of the data base schemes and the operators of the data manipulation languages. One figure, 11 bibliographic citations.

UDC 519.95

On One Approach to the Economy of Actions in Program Modeling
Manerko Yu.F., Eligulashvili B.G., PROGRAMMIROVANIYE, 1978, No 6.

An algorithm is given which permits reducing the modeling time for complex systems by virtue of increasing the efficiency of executing a time list of events.

UDC 681.3.06

Experiments with Hierarchical Substitution Algorithms
Broytman M.G., Kogan Ya.A., Peterson E.Ya., PROGRAMMIROVANIYE, 1978, No 6.

Hierarchical substitution algorithms based on a simulation model for the program processing in a computer system with a page organization of the memory are investigated. The influence of the parameters of the hierarchical algorithms on the page call rate from the peripheral memory is analyzed. The results of the modeling demonstrate that hierarchical substitution algorithms require fewer page callups than the LRU and FIFO algorithms which are the most widespread at the present time. Some 3 tables, 5 bibliographic citations.

UDC 681.3.06

The Static Identification of Procedures in ALGOL-like Language Compilers
Abramovich S.M., PROGRAMMIROVANIYE, 1978, No 6

A solution is proposed for the problem of determining the inadequate specifications for the formal parameters of procedures in compilers for ALGOL-like languages.

The solution considered here does not require the repeated running of the input program. Algorithms are given which are written in INSTR languages, as well as examples which illustrate their application. Some 4 figures, 9 bibliographic citations.

UDC 519.95

The Utilization of Logic Gate Language in the Design of Matrix Multiplier Circuits
Avdeyeva G.I., Kossovskiy V.G., PROGRAMMIROVANIYE, 1978, No 6.

An analysis is made of a matrix multiplication circuit using the language of the logic gates. A practical algorithm is given for the study of a matrix multiplier where the original multipliers are broken down into parts. Estimates are given for the equipment and the operational speed of the circuit. One figure, 5 bibliographic citations.

UDC 51:519.681,519.683

On the Application of a Formalized Technical Assignment Procedure to the Design of Processing Programs for Data Structures
Glushkov V.M., Kipitonova Yu.V., Letichevskiy A.A., PROGRAMMIROVANIYE, 1978, No 6.

A method is presented for the formalized technical assignments of program planning, and an example is given of a program set up using this method for processing data structures of a complex nature. Some 2 figures, 18 bibliographic citations.

UDC 681.3.058

Increasing the Efficiency of Ordering with the Method of Triangles
Vilenkin S.Ya., Charnaya I.S., PROGRAMMIROVANIYE, 1978, No 6.

Increasing the efficiency of the method of ordering a data array based on associative parallel processors is treated. For this, the elements of the data array being ordered are treated as ordered statistics and the maximal and minimal elements of the subarrays being ordered are compared. A transformation of the method of triangles is given, taking the results obtained into account. Some 2 tables, 5 bibliographic citations.

UDC 681.3.06.51

A Virtual Operational System for Small and Medium Computers
Sokol Yan, Navratil Vladimir, PROGRAMMIROVANIYE, 1978, No 6.

The organizational principle of a virtual operational system for small and medium computers are described. Many of the drawbacks of third generation small and medium computer operational systems are taken into account and overcome in the proposed operational system.

UDC 681.3.01

The Organization of a Controlled Memory when Programming in FORTRAN for the "Minsk-32" Computer
Konevskiy B.I., PROGRAMMIROVANIYE, 1978, No 6.

The article contains a description of the means which can be employed in developing FORTRAN programs on the "Minsk-32" computer for the organization of a controlled memory, i.e., a memory, the distribution of which is specified during the program and is realized in the process of running the program on the computer. The advantages of such a method are discussed as compared to the static procedure adopted in standard FORTRAN language. Some 2 tables, 3 bibliographic citations.

8225
CSO:1870

GEOPHYSICS, ASTRONOMY AND SPACE

'AIR & COSMOS' REPORTS ON 'SOYUZ-33' FAILURE

Paris AIR ET COSMOS in French No 766 (19 May 79) pp 49,56

[Unsigned article: "Revelations on the 'Soyuz-33' Failure"]

[Text] The Soviet press has provided various details on the mission failure of the "Soyuz-33" transport ship, which did not dock with the "Salyut-6" orbital station. The "Soyuz-33" international crew of Nikolay Rukavishnikov and Georgiy Ivanov (Bulgaria) safely softlanded on 12 April. Up to the approach phase, everything had been going normally. There were to be five burns of the "Soyuz-33" main engine. The first lasted 61 seconds without cause for worry: the engine burned steadily and provided a barely perceptible acceleration.

But during the approach the engine burned for only 3-4 seconds instead of the prescribed 61 seconds, and Nikolay Rukavishnikov--according to his comments after his return--noted that the thrust was irregular: "I got the impression the "Soyuz" was beginning to vibrate, but by extending my arm towards the control panel, I was able to make this phenomenon disappear; I did not exactly understand what was happening," said Rukavishnikov, "but I realized that the rendezvous might be abandoned." At that precise moment, "Soyuz-33" was three kilometers from the "Salyut-6" orbital station.

The "Soyuz-33" crew then fired the main engine three more times, but it was clear that the pressure in the combustion chamber was lower than prescribed; still, there was some doubt on the part of the cosmonauts as to the origin of the difficulty. It was not altogether impossible that the pressure gauges were providing false information.

It was then that Flight Director Aleksey Yeliseyev gave the order to abandon the mission as planned and to suit up... In the meantime, it was decided to continue flight in the automatic mode and to let the cosmonauts sleep. During this time, the ground crews made their diagnosis: there was a malfunction in the main engine. This was the first time in the history of Soviet spaceflight that such a malfunction had ever occurred.

The only solution was to use the back-up engine and, at worst, the orientation engines. There was some question as to whether there would be sufficient fuel reserves for these engines to deorbit the transport ship in order to ensure proper reentry through the dense layers of the atmosphere.

On the morning of 12 April, three possible variations based on the assumption that the back-up engine would function were given to the cosmonauts:

--if it burned for less than 90 seconds, "Soyuz" would remain in orbit and another maneuver would have to be worked out;

--if the engines burned for more than 90 seconds but less than the nominal 188 seconds, without any other maneuvers for four revolutions, "Soyuz" would reenter the atmosphere but would risk landing anywhere on earth. It would, therefore, be necessary to correct the trajectory with a manual maneuver;

--finally, if the burn lasted the nominal [188 seconds], reentry would go well.

Fortunately, this is what occurred. [5]

CSO: 3100

GEOPHYSICS, ASTRONOMY AND SPACE

PRINCIPLES OF CONTROL SYSTEMS FOR SPACECRAFT

Moscow SISTEMY UPRAVLENIYA POLETOM KOSMICHESKIKH APPARATOV in Russian 1978 pp 5-14

[Chapter 1 by G. G. Bebenin, B. S. Skrebushevskiy and G. A. Sokolov from the book "Sistemy Upravleniya Poletom Kosmicheskikh Apparatov" edited by G. G. Bebenin, Mashinostroyeniye]

[Text] Tasks and Principles in the Construction of Flight Control Systems for Spacecraft

1.1 Control System Tasks

Controlling the flight of a KA [spacecraft] is a complex process which depends on the tasks being resolved by the apparatus during its flight. In this book basically the tasks of controlling KA in near earth space will be examined; however, many of them may be used also for KA which are performing a controlled flight in the vicinity of other planets.

Under the controlled flight of a KA we shall include the directed change of its position in space. The process of controlling KA under normal circumstances includes determination and forecasting of its trajectory motion and the processing of control commands for its movement.

Determination of the law for controlling the flight of a KA demands an examination of a number of ancillary questions. Thus, for example, when planning research work in the area of earth surface photography in the visible spectrum for geologic investigations it is necessary to satisfy a large number of conditions: the surface of the earth being investigated should be illuminated by the sun; the lenses of the cameras should not be exposed to the sun; the moon's crescent should not fall within the equipment's field of view and so forth.

Already from this far from complete listing of conditions it is apparent that for flight control it is necessary not only to forecast the movement of the KA, but also calculate the coordinates of the sun and the moon at any moment in time, estimate the relative position of the KA and the region being investigated, consider the capabilities for communications with the control point and the data dump, etc. From the example examined it is apparent that along with the classical tasks of control:

controlling the movement of the KA center of mass;

control about the KA center of mass; and

estimating the precision of the control process,

it is necessary to examine a large class of ancillary tasks:

ballistic control support (determining orbital elements and their forecasting either by digital or analytical methods);

estimating the astro-ballistic flight conditions (calculating the coordinates of the sun and moon, the conditions of relative visibility of the KA and the control point, etc.).

Control is made significantly more complex when examining KA systems which are jointly fulfilling either a specific task or a group of tasks. When analyzing the characteristics of KA control systems there arises a number of essentially new problems, for example:

selection of the initial orbital construction for the KA system;

estimation of the deformation of the relative position of the KA under the influence of various types of perturbations (the moon, the sun and others);

estimating present relative position and the conditions of relative visibility; and

determining the control strategy for each piece of equipment within the system, taking into account their interrelationship.

Naturally, the solution of labor-consuming tasks in the computer sense cannot be accomplished only by on board EVM [computers]. As a rule, the bulk of these is accomplished on the computing devices of the ground control points, and therefore the question concerning the rational distribution of control functions amongst the ground and on board control complexes is very important. In so doing it is necessary to take into account the fact that the interrelationship amongst these complexes has characteristic peculiarities when controlling automatic and manned KA. In the first case, the exchange of information flows only between the technical control devices of the ground and on board complex, and in so doing the information is transmitted in a formalized form. In the second case, the exchange of information also takes place with the utilization of communications facilities between the personnel of the ground complex (control group) and the crew. In this manner, there arise two parallel control profiles. Moreover, in the second profile the information is not always transmitted in a formalized format. This circumstance, as well as the presence of a "manned crew" in the control loop, significantly complicates its theoretical investigation.

We shall examine in a somewhat formalized format the definition and solution of the flight control task for a KA. In the general case the condition for the successful solution of a KA flight control task is a combination of certain parameters, the values of which should be monitored and maintained with precise accuracy. There may be several of these parameters $\varphi_1, \varphi_2, \ldots, \varphi_i, \ldots, \varphi_n$. We shall arrange to describe their control functions.

The actual values of control parameters differ from those calculated. The reasons inducing these variations are also caused by inaccurate knowledge or calculations of directly observed physical laws. It is customary to call these perturbations and disturbances. We shall define a series of perturbations as: $Q_1, Q_2, \ldots, Q_i, \ldots, Q_k$.

The control system monitors either directly or indirectly the values of the control parameters and transmits them to the object under control, in this case the KA, which controls the actions $G_1, G_2, \ldots, G_i, \ldots, G_m$, which strive to eliminate the control parameter variations which arise. The control actions are formulated by the control system according to the equation

$$\bar{G}=\Phi_y(\bar{\varphi}, \bar{\varphi}^*, t), \tag{1.1}$$

where Φ_y is the control operator which is accomplishing a transformation of n-measured vectors $\bar{\varphi}, \bar{\varphi}^*$ and time t in m-measured vector G of the control actions; $\bar{\varphi}^*$ is the vector which determines the required values of the control parameters.

Under the influence of controlling and perturbing actions there results a change in control parameters. This change may be written in the form of an equation

$$\bar{\varphi}=\Phi_{01}(\bar{G}, t)+\Phi_{02}(\bar{Q}, t). \tag{1.2}$$

Here $\bar{Q}$ is the k-measured vector of perturbing influences which are determined by the equation

$$\bar{Q}=\Phi_s(\bar{\varphi}, t). \tag{1.3}$$

A combined solution of the equations (1.1), (1.2) and (1.3) allows one to study the mechanism for changing control parameters, as well as to determine the accuracy of control within a given operator Φ_y, which is characterized by the vector

$$\Delta\bar{\varphi}\{\Delta\varphi_1, \Delta\varphi_2, \ldots, \Delta\varphi_n\},$$

where $\Delta\varphi_i=\varphi_i-\varphi_i^*$.

This task is known in the theory of automatic control as an analysis task. In addition, the equations (1.1), (1.2) and (1.3) allow one to solve the task of synthesis which leads to the selection the operator Φ_y. For an unambiguous solution to this task it is necessary to supplement the designated system with a condition which flows out from the accepted criterion of optimization.

We shall examine the most characteristic features of KA flight control systems. Primarily it is their multiplicity and multi-connectedness. The appearance of the operators Φ_{01}, Φ_{02} and Φ_s in the flight process changes with respect to the change in physical conditions at each stage. Moreover, the control parameters and control actions are also being changed.

Thus, upon placing a KA into orbit the control parameters are the coordinates and component velocities of motion for the center of mass, as well as angular coordinates which determine the spatial orientation of the spacecraft body; control actions are the forces and moments which are being created by the engine of the carrier rocket and the steering devices. During motion in orbit for a non-maneuverable KA the angles which determine the orientation of the spacraft's body belong to the control parameters, and the control actions are the moments which are created by the control devices.

From that stated above it is apparent that at each stage it is necessary to apply different operators Φ_y. In so doing the very same controlling actions are created by the devices which are based on the utilization of various physical principles. Monitoring the control parameters at separate stages is also accomplished by specific measuring devices. Consequently, the diversity in the physical nature of the elements being used and the frequent changes to the composition and structure of the system, as well as the diversity of the structures should be noted as characteristic features of control systems.

When solving synthesizing tasks for a control system a large number of criteria are present, For example, maximum accuracy, minimum root-mean-square of error, minimum energy expenditures, minimum fuel consumption, maximum high-speed response, maximum amount of data which is received furing the flight, etc. Similar multi-dimensionality, as well as the multiplicity of structures noted above determine the multi-smoothness of scientific research into the questions of control.

1.2 General Principles in the Construction of a Ground Control Complex

A ground KA flight control complex includes a receive-transmitting tracking station (PPS) and a control center (TsU). In figure 1.1 there is presented a basic diagram for the control of spacecraft.

A network of receiver-transmitting stations performs the trajectory measurements, the reception of scientific and telemetry information in real time or from the recording of storage devices, as well as the transmission of commands to the spacecraft.

The control center performs the following basic tasks: planning the experiments which are being performed during the flight of the spacecraft; controlling the operation of the PPS; processing the measurement and telemetry information; forecasting the control commands for transmission to the spacecraft; monitoring and evaluating the functioning of the on board systems and the scientific instruments; evaluating the results of the experiments, etc.

The control centers are normally equipped with computer complexes consisting of either one or several EVM with programmable algorithmic systems (PAS).

Schematically the functioning of the system may be presented in the following manner. The ground PPS network measures the parameters of motion for the earth satellite in either an active or passive mode. Information of a different type appears for processing at specialized PAS through the program-algorithmic control system for data processing which is normally accomplished at the control computer complex.

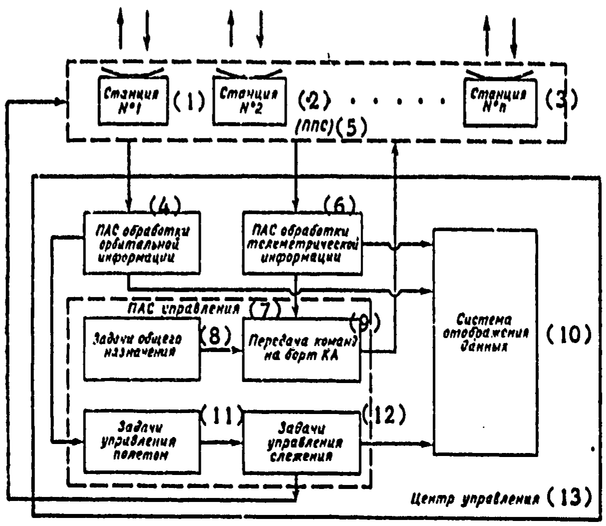


Figure 1.1. Schematic of a Ground Control Complex

Key:

1.	Station No 1	8.	General purpose tasks
2.	Station No 2	9.	Command transmission to the KA
3.	Station No n	10.	Data display system
4.	PAS orbital data processing	11.	Flight control tasks
5.	PPS	12.	Tracking control tasks
6.	PAS telemetry data processing	13.	Control center
7.	PAS control		

The program-algorithmic system for processing orbital information performs the transformation and initial processing of the tracking data. From this data the orbit of the KA is determined, refined and predicted as is the accuracy of its elements.

The program-algorithmic telemetry data processing system monitors the engineering status of the satellite's on board equipment and the correctness of its processing of commands and experiment programs; during the flight it performs error diagnosis, and in the event the latter does arise it works out the commands to eliminate these errors and determines the reasons for the malfunction in the KA elements and makes the decision concerning the switchover to reserve units or the termination of the conduct of the experiments.

A broad range of tasks is resolved by the control PAS. These tasks may be broken down into a number of groups: general purpose tasks; KA flight control tasks; tasks for controlling the process of control command transmissions to the KA spacecraft; and tasks controlling the process of tracking the spacecraft.

The tasks of the first group may include, for example, a selection of the date for launching the KA, planning the experiments and planning the work of the PPS which performs the communications with the spacecraft.

The tasks of the second group are intended to work out the flight control commands such as, for example, the execution of orbital maneuvers, the accomplishment of corrections, directing the research equipment towards any type of object, etc.

The tasks of the third group are of basically a technical nature. Nonetheless, the selection of a number of devices taking into account their technical capabilities and status, determination of the common communications frequencies and the adoption of measures during the anomalous reception of scientific and telemetric data concerning the status of the KA also falls under the competence of this group of tasks.

The tasks of the fourth group are more time consuming. In this case, there is organized a process for tracking the orbits which preceded, for example, a change in the orbital elements as a result of a correction and the order for collecting the orbital data is determined. In addition, the types of observations devices are selected, as well as the volume and qualitative composition of the measurements depending on the tasks being solved and taking into account the technical capabilities of the equipment. Within their competence there also falls the calculation of ephemerides for the KA, the sun, the moon, their accompanying polynomials, etc.

1.3 Principles in the Planning of Experiments On Board KA

When conducting research or performing specific tasks by one or several KA there arises the problem of planning the experiments and selecting the KA moments which will provide favorable conditions for the conduct of the experiments. To define this question concretely we shall examine several tasks which are being resolved by automatic research KA in near earth space: the investigation of the earth's natural resources; astronomical observations (for example, studying the spectra of stars in the absence of the earth's atmospheric interference, etc.); investigation of the sun (photography of the solar corona in white light, spectrography, studying solar flares, etc.); measuring radiation in near earth space; determining the frequency of collisions with meteorite particles, etc.

The already brief cross section of enumerated tasks attest to the fact that certain of these require the presence of specific conditions. Thus, the study of the earth's natural resources is tied in with photographing portions of the earth's surface in the visible spectrum. This is possible under conditions where these portions are illuminated, and the lunar disk is eliminated from falling within the camer's field of view. Astronomical observations of separate portions of the stellar sky are also impossible when solar illumination falls within the equipment's zone. In addition, there are frequently significant limitations of a temporary nature during the operation of a KA which may have an affect on the communications conditions between the spacecraft and the ground control point or communications with its KA relay craft. It is apparent that a favorable operating condition for a KA system to a significant degree depends on the time of day and seasonal variations (winter or spring), as well as the relative disposition of the KA and the ground control point. These factors result in the need for planning the experiments which are to be performed by the KA. We should immediately separate out two types of tasks. In the first case, one may examine the problem of selecting the moment of launch for the KA which satisfies the optimum, in whaterver sense, conditions for the conduct of the experiemtns, and in the second case a refinement of the conditions for conducting the experiments for the KA which has been inserted into its operational orbit. The taks of the second type, as a rule, lead to the usual calculations of the operating conditions for the research equipment of the KA and difficulties do not present themselves. In the very first case, the task of selecting the moment of launch offers specific difficulties and is associated with time-consuming calculations. Let us examine several of the more detailed possible methods for solving the first task.

Depending on the research program the conditions for conducting the experiments may be divided into two classes. To the first class we may assign the decisive conditions, and to the second -- the secondary conditions.

The infringement of conditions of the first class over any type of time intervals (for example, the sun's falling within the equipment's field of view, etc.) makes the conduct of a number of experiments impossible. The infringement of conditions for the second class may somewhat worsen the conditions for conducting the experiments, but does not disrupt them completely. We shall adopt the following designations: t_{st} is the desired instant of launch for the KA; $[t_a, t_b]$ is the time interval for the possible launch containing the moment t_{st}; $[t_s, t_d]$ is the assigned time interval for performing the experiment $(t_s > t_b)$; $\overline{\Pi} = (\Pi_1, \ldots, \Pi_\nu; \Pi_{\bar{1}}, \ldots, \Pi_{\bar{\nu}})$ is the vector of the parameters which specify the breakdown of the large number of experiment conditions into two classes;

$$\Pi_\nu = \begin{cases} 1 \text{ if the condition relates to the first class;} \\ 0 \text{ if the condition relates to the second class;} \end{cases}$$

$F_{\Pi}(t)$ is the total time losses as the result of the nonfulfillment of conditions of the first class;
$F_{\bar{\Pi}}(t)$ is the total time losses as the result of the nonfulfillment of conditions of the second class;

$I^v \cdot \{I_l^v\}$ is a regulated large group of intervals on which the condition is not performed (these intervals belong to $[t_s, t_d]$), we shall derive

$$|I_l^v| = (t_n^v - t_l^v)_l, \tag{1.4}$$

where t_l^v, t_n^v is the beginning and end of the intervals; and l is the number of the interval.

The total time losses during the interval examined is $[t_s, t_d]$ as a result of the nonfulfillment of conditions of the first and second classes which are equal to

$$F_\Pi(t) = \sum_l |I_l^v|; \tag{1.5}$$

$$F_\Pi(t) = \sum_l |\bar{I}_l^v|. \tag{1.6}$$

We shall examine the specific task of planning experiments when it is necessary to fulfill the conditions

$$F_\Pi(t) \to \min t \in [t_a, t_b].$$

In this case there exists an extreme unidimensional task, the specific nature of which consists of the fact that the function $F_\pi(t)$ may be determined algorithmically. Let us assume that over large time intervals the function $F_\pi(t)$ is polyextremal, and over small intervals is unimodal. One may break down the interval $[t_a, t_b]$ into a series of subintervals $\{t_{ap}, t_{bp}\}$, the duration of which $<n_n$ hours.

Then we have

$$\min F_\Pi(t) = \min \min F_\Pi(t), \tag{1.7}$$

$$t \in [t_a, t_b],\ 1 \leqslant p \leqslant \bar{p},\ t \in [t_{ap}, t_{bp}],$$

that is the original task leads to a determination at each subinterval $\{t_{ap}, t_{bp}\}$ of such a point t_p for which the following relationship is true

$$F_\Pi(t_p) = \min F_\Pi(t),\ t \in [t_{ap}, t_{bp}] \tag{1.8}$$

with the following selection within the large quantity $\{t_p\}$ of such a point t_p*, for which the following relationship is true

$$F_\Pi(t_p) = \min F_\Pi(t),\ 1 \leqslant p \leqslant \bar{p}. \tag{1.9}$$

For the solution of such a task one may adopt the Fibbonachiyev plan of search for the extremal point.

It should be noted that the solution of planning tasks demands a significant amount of computer work which is tied in both with evaluating the function $F_\pi(t)$, and with the process of searching for the extremal point.

Even the brief cross section indicated above of conditions for conducting experiments shows the necessity for time consuming calculations tied in with, for example, determing the orbital elements, their prediction over the time interval being examined, calculating the lighting conditions, the conditions for illuminating the KA equipment, the mutual visibility of the KA and the control point and so forth. In addition, while planning the experiment one may achieve a significant increase in the efficiency of utilizing the space equipment for research.

1.4 General Principles for Constructing an On Board Control Complex

An on board control complex for an automatic KA, the functional schematic of which is presented in figure 1.2, includes an orientation and stabilization system (SOS) and a maneuvering control system (SUM). Coordinating the operation of these systems is accomplished by an on board digital computer (BTsVM).

The command signals in the BTsVM may be produced autonomously in accordance with the programmed flight and are stored within its memory unit, or in accordance with the ground command control complex. These commands are accepted by the receiving device (PU) of the radio command link (KRL).

On manned KA the on board control complex contains supplementary elements which make possible the active participation of the crew in the control process. As is shown in the functional schematic figure 1.3, additionally there are included within the control complex a system for displaying information (SOI) and a control console (PU). The SOI provides the crew with necessary flight-navigational information, information concerning the condition of elements within the control complex, as well as information concerning the functioning of the BTsVM. On the PU are placed the instru-

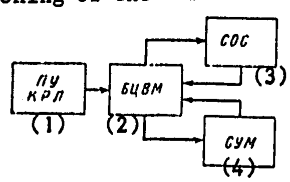


Figure 1.2. Functional Diagram for an On Board Control Complex of an Automatic KA

Key:
1. PU KRL
2. BTsVM
3. SOS
4. SUM

ments for manual control which provide for the output of commands directly into the orientation ans stabilization system and into the maneuvering control system. Through the PU the crew may input the necessary commands into the BTsVM.

A characteristic peculiarity of on board control complexes for manned KA is the necessity for the optimum combination of these manual control loops, as well as a display system for flight-navigational information, the pilot-cosmonaut and the organs for manual control (control handles). This task is integral to the "man-machine" problem.

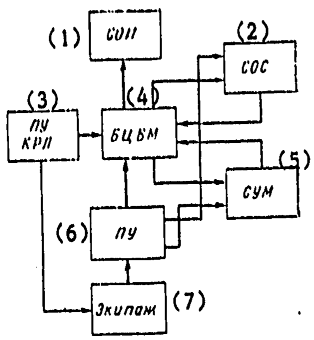
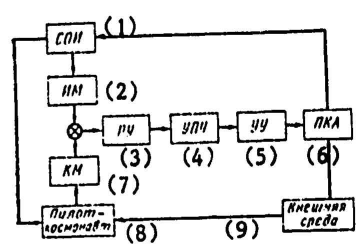


Figure 1.3. Functional Diagram for an On Board Control Complex of a Manned KA

Key:
1. SOI
2. SOS
3. PU KRL
4. BTsVM
5. SUM
6. PU
7. Crew

When manually controlling the KA, the pilot-cosmonaut receives information in the form of coded signals from indicators which in combination form the SOI of the external environment. Based on this information and information which includes its centra; nervous system in the form of information concerning the control process (its basic characteristics), the pilot-cosmonaut formulates the so called conceptualized model (KM) which describes the series of laws of conduct (action) which have been acquired as a result of training according to the control of the KA under specific concrete conditions (figure 1.4). In so doing he constantly compares his own conceptualized mode with the data model (IM) which is being formulated by the SOI on the basis of information from the measuring instruments. Based on the comparison of these models the pilot actuates the control handle (RU) also through amplifying-transfer (UPU) and control (UU) devices on the KA.

Figure 1.4. Functional Diagram of KA Manual Control



Key:
1. SOI
2. IM
3. RU
4. UPU
5. UU
6. PKA
7. KM
8. Pilot-cosmonaut
9. External environment

Important positive qualities for a manual control system are its high reliability and adaptability. The first is explained by the fact that the pilot-cosmonaut may control the KA even in the case of SOI malfunctions (in the absence of instrument data) with the aid of information received only from the external surroundings (the presence of a reserve control loop). The property of adaptability consists in the fact that in the control process the KM is constantly being refined. In addition, the manual control system includes in the form of a memory data concerning the conduct of the control object and the rules of action in the most varied situations which significantly differ from the normal flight mode.

The efficiency of the manual control loop to a signficant degree is determined by the quality of the data model of the reproducible SOI. The data model should as adequately as possible reproduce the KA's motion dynamics. Therefore, the following factors play a significant role: the appearance and form of the indexing parameters; the methods for combining on a single indicator groups of parameters; the placement of indicators on instrument panels; and the correlation logic for the information display methods on the indicators and the control organs.

The control parameters should be reproduced by the SOI in both the appearance and form most suitable for reception by the pilot. The indicators for the most important parameters should be placed closest to the center of the instrument panel. The most acceptible appearance and form for displaying information in this case, apparently, is the appearance and form for indicating roll, yaw and pitch angles which are received in the instruments of the "flight horizon" type.

In constructing the correlation logic for the data display methods and control organs it is necessary to take into account the basic requirement of engineering psychology: the direction of movement for the control organ should correspond to the direction movement of the active indicator element. As a result of an action on the KA of a corresponding control moment the yaw angle will decrease, and the active indicator element will rotate counter-clockwise or it will move to the left.

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GEOPHYSICS, ASTRONOMY AND SPACE

SPACE VEHICLE FLIGHT CONTROL

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[Text] Control of Satellite Systems

8.1 Application of Satellite Systems

One of the main directions of present-day development of space technology is the creation and commercial use of specialized satellite systems (SS) in the interests of [13,44] global communications, meteorology and climatology, geodesy and navigation, controlling aircraft movement, reconnaissance of the earth's natural resources and so forth.

Satellite Communications Systems. In 1964, there was organized the International Consortium for Communications Satellite Systems (SSS) -- Intelsat which supported the creation in 1969 of the global SSS for the orbiting and geostationary placement of ISZ [artificial earth satellites] over the Atlantic, Pacific and Indian Oceans.

At the present time, this system features four fourth generation Intelsat-4 geostationary ISZ which are equipped with systems for orbital correction, orientation and stabilization. The launching of a second series consisting of four ISZ of this type is proposed. Apart from the global communications systems there exist and are being created regional SSS, which are intended to service the territory of a given country or group of countries.

Meteorological Satellite Systems. The utilization of ISZ in the interests of meteorology began in 1960 with the launch of ISZ Tiros-1. The most interesting results from the point of view of refining on board and ground equipment, recording, transmission, reception and processing of meteorological data, as well as the selection and rationale for the structure of the global meteorological satellite systems was derived during the realization of the Tiros-Nimbus and Itos programs.

Geodetic and Navigational Satellite Systems. Geodetic and navigational satellite systems are intended to refine our description of the earth's shape, determine with a high degree of accuracy the characteristics of the geopotential, improve the geodetic network, the precise determination of the locations of submarines, ships, spacecraft and aircraft, the synchronization of world time and so forth.

Satellite Systems for Controlling Aircraft Movement. In August 1971, in Madrid between the U.S. and the European Organization for Space Research (ESRO), which includes 10 west European countries, an agreement was reached concerning the conduct of joint research in the creation of a worldwide satellite system for controlling the movement of aircraft (UVD). For the functioning of such a system 12 ISZ would be needed, the entire world's inventory of transport aircraft would have to be reequipped and a new network of ground stations would have to be created.

Aside from the global ISZ systems for use in aerial navigation in individual countries, and primarily in the U.S.A., there is being discussed the use of regional systems with the objective of insuring flight safety. Three tasks are charged to these systems: determining the locations of the aircraft, navigation and communications. At the basis of the system lies the relay by satellites of aircraft signals to the ground station. Four ISZ are sufficient in order to determine precise coordinates and time.

Satellite Systems for Reconnaissance of the Earth's Natural Resources. The problem of preserving our surrounding environment and the rational use of natural resources has acquired at the present time an international character. Its solution requires a complex approach which is based on the concentration of the efforts of scientists and engineers throughout the entire world, on the attraction of an entire arsenal of engineering achievements and, primarily, the achievements in the area of space technology.

The outstanding advantage of satellite systems over others (aircraft, balloons-probes, sounding rockets, etc.) is contained in the fact that they ensure regular global coverage and the reception of uniform data from broadest regions.

The selection of ISZ orbits for the investigation of the earth's resources depends on the indicated tasks. A sun synchronous orbit from the highest altitude ensures total coverage of the earth's surface for several weeks; a geostationary orbit ensures constant coverage of a large territory, although the exceedingly great altitude of this orbit makes more difficult the reception of high resolution imaging.

8.2 Synthesis of a Satellite System

The control of a satellite system is an immeasurably more complex task than controlling the flight of each KA being examined separately. This is dictated by a large number of factors. First of all, if one is to understand that under SS there is a series of spacecraft intended for the joint solution of a predetermined number of tasks, then controlling the flight of SS is controlling the flight of each KA consistent amongst each other. A similar approach leads to a significant increase in the spatial scale of control parameters and the appearance of new algebraic and differential bonds.

On the other hand, servicing the SS is accomplished [29] with the aid of extremely cumbersome and technically complex ground and on board equipment (on board communications equipment for the reception and transmission of scientific data, relay, monitoring the status of equipment, controlling orientation and stabilization, orbital correction and so forth; a network of tracking stations, the reception of scientific and telemetric data, the transmission of commands to the spacecraft; the center for controlling and processing data and so forth). In this manner, strictly speaking, controlling SS together with purely ballistic control of a KA includes controlling a network of receiver-transmitting stations, controlling the processing of data in the control center, and finally, autonomous control. Here it is not intended that we examine the entire complex of control tasks for SS, and what is more, from the large number of tasks for ballistic control of SS we shall undertake to try and present only those which border on the problem of synthesizing a satellite system [2,34], which is intended for the uninterrupted servicing of a series of points located on the surface of the earth.

Understood within the task of synthesizing SS we shall include the task of determining the initial orbital construction of the system and the strategy for correcting the orbit of each KA with the objective of optimizing the characteristics of continuous servicing of a given series of points at a fixed time interval [a,b].

The orbital construction of a satellite system is determined totally when $t=t_0$ by the initial values of the semimajor axis a_j^0, eccentricity e_j^0, inclination (i_j^0), argument of perigee (ω_j^0), the geographic longitude of the ascending node L_j^0 and the longitude of the ascending node Ω_j^0 for each j-th KA included in the system (j=1, 2, ..., j). With the passage of time the natural evolution of the KA's parameters of motion result in a deformation of the satellite system, that is to a change in the relative position of the KA in space which may be undesired from the point of view of efficiency in the solution of a problem which stands before the SS. Compensation for these effects is accomplished normally with the aid of a correction in the motion parameters of the KA.

Servicing of the assigned points on the earth's surface is accomplished by each KA at a certain time interval usually designated as a work zone (RZ). The beginning and end of the RZ is a function of many factors: orbital elements, the relative position of the KA, the sun, the moon, the servicing points, communications points, the control center, and finally, the technical parameters of the number of devices on board the KA, etc.

We shall define the time cycle (VTs) in the functioning of SS as the interval of time the edges of which correspond with the beginning of two neighboring work zones of one or another, for example, of the first KA (figure 8.1).

The interval [a,b] may be covered by an ordered sequence of time cycles which have been assigned the index n(n=1, 2, ..., n). In the future for RZ of the j-th KA on an n-th time cycle we shall utilize the designation (t^n_{ij}, t^n_{kj}).

We shall introduce a number of suppositions and proposals: the quantity of KA systems is given and is equal to $\bar{J}$; equipment malfunctions with the KA system are not to be considered; the ranges of variation for the initial values of the orbital parameters of each KA a_j^0, e_j^0, i_j^0, ω_j^0, L_j^0 and Ω_j^0 are assigned:

$$a_j^{0-} \leqslant a_j^0 \leqslant a_j^{0+};$$
$$\cdots\cdots\cdots \qquad (8.1)$$
$$\Omega_j^{0-} \leqslant \Omega_j^0 \leqslant \Omega_j^{0+};$$

$j_1 < j_2$ causes $\Omega_{j1}^0 < \Omega_{j2}^0$;
to each time cycle there belongs only a single RZ for each KA;

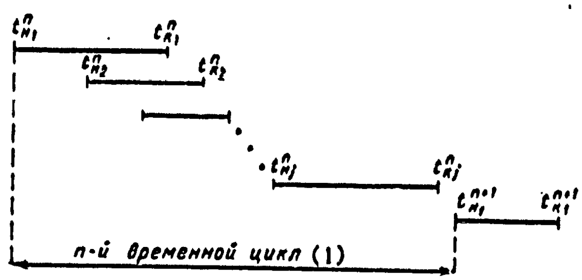

Figure 8.1. Time Cycle for the Functioning of SS

Key:
1. N-th time cycle

when $t^n_{\text{н}j} > t^n_{\text{н}m}$, then $t^n_{\text{к}j} > t^n_{\text{к}m}$ ($t^n_{\text{н}j} > t^n_{\text{н}m}$ when all $n, j > m$).
within each work zone of the j-th KA there is accomplished a simultaneous servicing of all points;
the plan for correcting the motion parameters of the KA is given;
the magnitude of the correction impulse and the "energy" reserve on board the KA limited.

Under the indicated suppositions and proposals the constancy of servicing is more or less the total duration of H intervals free from servicing.

Let us examine on the n-th VTs two adjacent RZ corresponding to the j-th and (j+1)-th KA. Two situations are possible: a) $t^n_{\text{н}j+1} > t^n_{\text{к}j}$ and b) $t^n_{\text{н}j+1} \leqslant t^n_{\text{к}j}$.

In situation a the given work zones are separated by an interval free of servicing, the duration of which $H^n_{j,j+1}$ equals

$$t^n_{nj+1} - t^n_k > 0;$$

in situation b this interval is absent, that is its duration equals zero.

Thus, we formalize

$$H^n_{j,j+1} = \max(0,\ t^n_{nj+1} - t^n_{kj}).$$

Consequently, the duration of the intervals freed from servicing at the n-th VTs is

$$H^n = \sum_{j=1}^{\bar{J}-1} \max(0,\ t^n_{nj+1} - t^n_{kj}) + \max(0,\ t^{n+1}_{n1} - t^n_{k\bar{J}}). \tag{8.2}$$

Finally,

$$H = \sum_{n=1}^{\bar{n}} H^n = \sum_{j=1}^{\bar{J}-1} \sum_{n=1}^{\bar{n}} \max(0,\ t^n_{nj+1} - t^n_{kj}) + \sum_{n=1}^{\bar{n}} \max(0,\ t^{n+1}_{n1} - t^n_{k\bar{J}}). \tag{8.3}$$

If we define the magnitude of the correction impulse which is realized at the n-th VTs for the j-th KA through ΔV_j^n, then, apparently the values t^n_{nj} and t^n_{kj} may be presented in the form of certain functions from

$$a^0_j,\ e^0_j,\ i^0_j,\ \omega^0_j,\ L^0_j,\ \Omega^0_j \text{ и } \Delta V^1_j,\ \Delta V^2_j, \ldots,\ \Delta V^{\bar{n}}_j.$$

Consequently, the function H, which is being accepted by us as a function of the objective of the synthesizing task, depends in the final calculation on

$$a^0_j,\ e^0_j, \ldots,\ \Omega^0_j,\ \Delta V^1_j,\ \Delta V^2_j, \ldots,\ \Delta V^{\bar{n}}_j,\ j = 1,\ 2, \ldots,\ \bar{J},$$

that is

$$H = H(Э^0_1,\ Э^0_2, \ldots,\ Э^0_{\bar{J}},\ V_1,\ V_2, \ldots,\ V_{\bar{J}}), \tag{8.4}$$

where for frequent writing we utilize

$$Э^0_j = \| a^0_j,\ e^0_j,\ i^0_j,\ \omega^0_j,\ L^0_j,\ \Omega^0_j \|^T,\ V_j = \| \Delta V^1_j,\ \Delta V^2_j, \ldots,\ \Delta V^{\bar{n}}_j \|^T,$$

where T is the transposition sign.

The main limitations of the synthesizing task are the differential equations of KA motion (see chapter 2), which in vector notations have the form

$$\frac{dЭ^n_j}{dt} = F_j(Э^n_j,\ \Delta V^1_j,\ \Delta V^2_j, \ldots,\ \Delta V^n_j,\ t),$$
$$Э^n_j(t_0) = Э^0_j,\ n = 1,\ 2, \ldots,\ \bar{n},\ j = 1,\ 2, \ldots,\ \bar{J}, \tag{8.5}$$

where $Э_j^n(t)$ is the rule of change at the time of the vector for the orbital elements of the j-th KA at an interval equal to n of the time cycle.

The equations (8.5) far from exhaust the entire multitude of restrictions in the task of synthesizing. Above we were reminded of the restrictions which were connected with the functional conditions of the KA equipment, with the magnitude of the correction impulse and the "energy" reserve. Of great significance also are the restrictions which result from determining the work zones and so forth. All of these conditions we present in the most general form:

$$\vartheta_j^0 \in A_\vartheta, \quad V_j \in A_V, \tag{8.6}$$

where A_ϑ and A_V are suitable allowable numbers.

In this manner, we received the task of synthesizing SS which led to determining the vectors ϑ_j^0 and V_j for all $j=1, 2, \ldots, \bar{J}$, and the minimizing function (8.4) under the restriction of (8.5) and (8.6).

It is appropriate to note that under the task of synthesizing one may also include the task of minimization of $\bar{J}$ under the restrictions (8.5) and (8.6) and

$$H(\vartheta_1^0, \vartheta_2^0, \ldots, \vartheta_{\bar{J}}^0, V_1, V_2, \ldots, V_{\bar{J}}) \leqslant H^*,$$

where H* is an assigned constant.

It is easy to see that this task leads to the solution of a series of tasks (8.4) - (8.6) for a number of values of j.

Unfortunately at the present time sufficiently effective precise methods for solving the task of synthesis (8.4) - (8.6) do not exist, therefore hereinafter we shall dwell on certain of its exceptional cases which will allow us to construct an approximate procedure to search for the solution even in a general case.

In the first special case we shall propose that the strategy for correction is fixed. In the second special case we shall assume that the orbital construction is fixed. The two tasks examined below correspond to this case. In selecting the strategy for correcting the motion parameters for the spacecraft of a system their joint coordination is essential from the point of view of maintaining constant servicing to the assigned points on the earth's surface by the satellite system as a whole. It is this very peculiarity which significantly complicates the task that led to the basic reason for a two-stage approach to the problem, when at the first stage an ideal correction law for the system as a whole is constructed, and in the second the actual rule for the correction of motion parameters for each KA which is examined in isolation.

On the basis of those methods and algorithms for resolving the named tasks which will be presented in the following paragraphs there lies the knowledge of the laws of the evolution of KA motion parameters in time and considers their peculiarities for each orbital element.

8.3 The Evolution of Satellite Systems

The long lifetime of satellites may be the result of changing the initial structure of the network. At the same time, the disruption of the structure may be substantial and would worsen the conditions for performing the established tasks. The ballistic stability of the system may serve as a measure for the stability of the satellite system's structure. Under the ballistic stability of a system we shall understand in the future its capability to retain its initial structure within established limits over long intervals of time.

It should be noted, that every system of satellites it characterized by its ordered structure, that is the ordered relative position of the satellites. The relative mutual position of the satellites may, for example, be characterized by a series of three angles i_j, Ω_j, u_j ($j=1, 2, \ldots, n$), where n is the number of satellites within the system. The relative position of adjacent satellites within a system at a random moment in time may, for example, be characterized by the values

$$(\Delta\varkappa_{j+1,j})_t = \varkappa_{j+1} - \varkappa_j, \quad \varkappa_j = i_j, \Omega_j, u_j. \tag{8.7}$$

Under the influence of a different type of perturbations there will occur a change in the values which have been determined by the formula (8.5), and deviations will appear in the initially selected structure

$$\delta(\Delta\varkappa_{j+1,j}) = (\Delta\varkappa_{j+1,j})_t - (\Delta\varkappa_{j+1,j})_{t0}, \tag{8.8}$$

where $(\Delta\varkappa_{j+1,j})_{t0}$ are the characteristics of the relative position j+1, j-x of the satellites of the system at the initial moment of time.

A change in the initial structure may be caused by various perturbations of a specific nature. The main ones of these are: the difference in the earth's gravitational field from the central field; the braking influence of the atmosphere; the influence of external bodies, etc.

Below we shall limit ourselves to an examination of a system of satellites moving at great altitudes where the braking influence of the atmosphere is insignificant.

Influence of the Geopotential. To evaluate the influence in the distinction between the geopotential and the central potential on the stability of a KA system structure we shall perform an analysis of the age old perturbations of orbital elements. To accomplish this we shall make use of the initial equations (2.59) and hypotheses concerning the normal geopotential. As perturbation characteristics in the beginning we shall examine the increases in the elements $\delta p, \delta e, \ldots, \delta i$ for each revolution of the orbit. Considering that in (2.60) $\gamma \approx 1$, $g_0 = \mu/r^2$, the approximate changes in the orbital elements for a single revolution will be written as

$$\left.\begin{aligned}
\delta p &= \int_0^{2\pi} \frac{T_f}{g_0} 2r d\vartheta;\\
\delta e &= \int_0^{2\pi} \left\{ \frac{S_f}{g_0} \sin\vartheta + \frac{T_f}{g_0} \left[\left(1+\frac{r}{p}\right)\cos\vartheta + e\frac{r}{p} \right] \right\} d\vartheta;\\
\delta\omega_\pi &= \int_0^{2\pi} \left[-\frac{S_f}{g_0}\frac{\cos\vartheta}{e} + \frac{T_f}{g_0}\frac{1}{e}\left(1+\frac{r}{p}\right)\sin\vartheta - \frac{W_f}{g_0}\frac{r}{p}\operatorname{ctg} i \sin u \right] \times\\
&\quad \times d\vartheta;\\
\delta\Omega &= \int_0^{2\pi} \frac{W_f}{g_0}\frac{r}{p}\frac{\sin u}{\sin i} d\vartheta;\\
\delta i &= \int_0^{2\pi} \frac{W_f}{g_0}\frac{r}{p}\cos u\, d\vartheta
\end{aligned}\right\} \quad (8.9)$$

(when calculating the geopotential the symbol f is substituted for G).

In deriving the functions (8.9) we proceeded from the hypotheses concerning the small magnitude of the ratios $\frac{S_f}{eg_0}, \frac{T_f}{eg_0}, \frac{W_f}{eg_0}$. Therefore, for orbits with $e \to 0$ the given functions may turn out to be unsuitable.

In view of the fact that the values of perturbing accelerations for a normal geopotential are equal (2.54) and having first presented them in the form

$$\left.\begin{aligned}
S_0 &= \frac{\varepsilon_1}{r^4}(3\sin^2 i \sin^2 u - 1) = -\frac{\varepsilon_1}{2r^4}\left[3\sin^2 i \sin 2\left(u+\frac{\pi}{4}\right) + \right.\\
&\qquad \left. + 2 - 3\sin^2 i\right];\\
T_0 &= -\frac{\varepsilon_1}{r^4}\sin^2 i \sin 2u;\\
W_0 &= -\frac{\varepsilon_1}{r^4}\sin 2i \sin u,
\end{aligned}\right\} \quad (8.10)$$

where $\varepsilon_1 = -\frac{3}{2}\mu c_{20} r_{c3}$ are the approximate values for the change in the elements of an eliptical orbit for a revolution (taking into account that $g_0 \approx \mu/r^2$) we shall record it in the [46]

$$
\left.
\begin{aligned}
&\Delta p = -\frac{2}{p}\frac{\varepsilon_1}{\mu}\sin^2 i\int_0^{2\pi}(1+e\cos\theta)\sin 2u\,d\theta,\\
&\Delta e = \frac{1}{p^2}\frac{\varepsilon_1}{\mu}\int_0^{2\pi}\{\sin\theta\,(1+e\cos\theta)^2(3\sin^2 i\sin^2 u-1)-\\
&\qquad-[2\cos\theta+e(\cos^2\theta+1)](1+e\cos\theta)\sin^2 i\sin 2u\}\,d\theta;\\
&\delta\omega_n = \frac{1}{p^2}\frac{\varepsilon_1}{\mu}\int_0^{2\pi}\Big[-\frac{\cos\theta}{e}(1+e\cos\theta)^2(3\sin^2 i\sin^2 u-1)-\\
&-\frac{2+e\cos\theta}{e}(1+e\cos\theta)\sin\theta\sin 2u\sin^2 i+2(1+e\cos\theta)\times\\
&\qquad\qquad\times\sin^2 u\cos^2 i\Big]\,d\theta,\\
&\Delta\Omega = -\frac{2}{p^2}\frac{\varepsilon_1}{\mu}\cos i\int_0^{2\pi}(1+e\cos u)\sin^2 u\,d\theta,\\
&\quad-\frac{1}{p^2}\frac{\varepsilon_1}{\mu}\sin 2i\int_0^{2\pi}(1+e\cos\theta)\cos u\sin u\,d\theta.
\end{aligned}
\right\}
\qquad (8.11)
$$

To calculate the correct components we shall use the property of determinate integrals [46]

$$\int_0^{2\pi}\sin^n(x+\alpha)\cos^m(x+\alpha)\,dx=0, \qquad (8.12)$$

even if one of the whole numbers n or m is uneven and

$$\int_0^{2\pi}\sin^n x\cos^m x\sin^p(x+\alpha)\cos^q(x+\alpha)\,dx=0, \qquad (8.13)$$

then the sum of the whole numbers n+m+p+g is uneven.

The integration (8.11), taking into account (8.12) and (8.13), yields the results (without a conclusion the final results were presented in chapter 4)

$$\Delta p=\Delta e=\Delta i=0;\ \Delta\omega_n=\frac{\pi}{p^2}\frac{\varepsilon_1}{\mu}(5\cos^2 i-1);\ \Delta\Omega=-\frac{2\pi}{p^2}\frac{\varepsilon_1}{\mu}\cos i. \qquad (8.14)$$

The formulae (8.14) allow one to make certain qualitative conclusions. Firstly, the structure of the KA system is more stable in the field of a normal geopotential when the orbits feature identical geometry and similar inclinations. From(8.8) it follows that

$$\delta\Omega_{j+1,j}(t)\approx 0;\ \delta\omega_{nj+1,j}(t)\approx 0, \qquad (8.15)$$

if $(p_j)_{i0}\approx(p_{j+1})_{i0}$, $(i_j)_{i0}\approx(i_{j+1})_{i0}$, j is the number of KA within the system.

In addition, analysis of the formula for changing the argument of perigee shows that when the values of the inclination angle are equal to

$$i_{кр1}=\arccos\sqrt{\frac{1}{5}}\approx 63°26'; \; i_{кр2}=\pi-i_{кр1}\approx 116°34', \qquad (8.16)$$

the magnitude $\Delta\omega_п=0$.

The inclination angle values which correspond to (8.16) are called critical. From what has been said it follows that if the functional conditions for a communications system allow for the fulfillment of the established task, etc., then it follows that the orbital inclination angle of the KA system should be selected close to the critical one. Analysis of the formula (8.14) allows also for the evaluation of the shifting of an argument of perigee for orbits whose inclinations differ from the critical ones. Thus, when $i<i_{кр1}$ и $i>i_{кр2}$, $\Delta\omega_п>0$ of the perigees are shifted in the direction of satellite motion, then when $i_{кр1}<i<i_{кр2}$, $\Delta\omega_п<0$ of the perigees are shifted in the direction opposite to the direction of flight. The displacement of the perigee achieves its maximum for an orbit with an inclination close to zero (for equatorial orbits and for low-flying satellites the displacement may reach ~1.2 degrees per revolution [46]).

The Influence of External Bodies. To evaluate the influence of external bodies we shall make use of the functions (4.39) - (4.42). In practical tasks when calculating the values of $\alpha_j, \beta_j, \gamma_j$ we shall make use of array representations. Let $r_н^0$ be a single vector which determines the direction towards the perturbing body. The projection $\bar{r}_н^0$ on the axis of the system $O_0X_\omega Y_\omega Z_\omega$ is determined by the formula

$$\bar{\xi}=D_1\bar{u}_1, \qquad (8.17)$$

where

$$\bar{\xi}=\begin{vmatrix}\xi_1\\ \xi_2\\ \xi_3\end{vmatrix}; \; \bar{u}_1=\begin{vmatrix}\cos u_к\\ \sin u_к\end{vmatrix}. \qquad (8.18)$$

The matrix

$$D_1=\begin{vmatrix}d_{11} & d_{12}\\ d_{21} & d_{22}\\ d_{31} & d_{32}\end{vmatrix} \qquad (8.19)$$

may be presented in the form of the three matrices

$$D_1=CBA, \qquad (8.20)$$

where matrix A determines the projection of the vector $\bar{r}_н^0$ on the axis of the geocentric inertial coordinate system $O_нX_нY_нZ_н$; matrix B determines the transition from the $O_нX_нY_нZ_н$ system to the $O_0X_1Y_1Z_1$

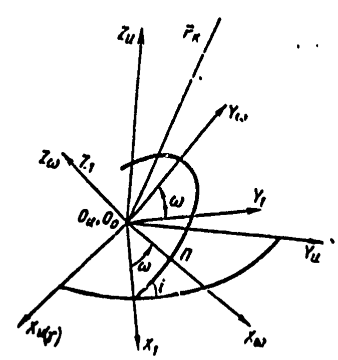

Figure 8.2. Coordinate Systems

coordinate system, one of the axes which is directed towards the ascending node of the satellite's orbit, the second axis is orthogonal to the first and lies within the satellite's orbital plane and the third is normal to the KA's orbital plane (figure 8.2). Matrix C determines the transfer from the $O_0X_1Y_1Z_1$ coordinate system to the $O_0X_\omega Y_\omega Z_\omega$ ... is directed towards the pericenter of the KA orbit:

$$A = \begin{vmatrix} \cos\Omega_к & -\sin\Omega_к\cos i_к \\ \sin\Omega_к & \cos\Omega_к\cos i_к \\ 0 & \sin i_к \end{vmatrix}; \quad (8.21)$$

$$B = \begin{vmatrix} \cos\Omega & \sin\Omega & 0 \\ -\sin\Omega\cos i & \cos\Omega\cos i & \sin i \\ \sin\Omega\sin i & -\cos\Omega\sin i & \cos i \end{vmatrix}; \quad (8.22)$$

$$C = \begin{vmatrix} \cos\omega_п & \sin\omega_п & 0 \\ -\sin\omega_п & \cos\omega_п & 0 \\ 0 & 0 & 1 \end{vmatrix}. \quad (8.23)$$

The presentation of the vector $\bar{\xi}$ in the form (8.18) is convenient for its differentiation and time integration or for the parameter u_k. From an integration of the area we derive

$$\frac{du_к}{dt} = b_к\Delta_к^2, \quad (8.24)$$

where $b_к = \frac{2\pi}{T_к\varepsilon_к^{3/2}}$, $\varepsilon_к = 1 - e_к^2$, $\Delta_к = 1 + e_к\cos(u_к - \omega_к)$.

Here T_k is the rotational period of the perturbing body around its central body.

From (8.18) and (8.24) it follows that

$$\frac{d\bar{\xi}}{dt} = \begin{vmatrix} \frac{d\xi_1}{dt} \\ \frac{d\xi_2}{dt} \\ \frac{d\xi_3}{dt} \end{vmatrix} = D_1\frac{du_1}{dt} = b_к\Delta_к^2 D_1\frac{du_1}{du_к} = b_к\Delta_к^2 D_1 \begin{vmatrix} -\sin u_к \\ \cos u_к \end{vmatrix}. \quad (8.25)$$

The formulae (8.21), (8.22), (8.23) and (8.25) make it possible to calculate the values α_j, β_j, γ_j и $\frac{d\beta_j}{dt}$, input into the system of equations (4.40) - (4.42). It is also convenient to use the following vector designations

$$\bar{\alpha} = \begin{vmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{vmatrix}, \quad \bar{\beta} = \begin{vmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_5 \end{vmatrix}, \quad \bar{\gamma} = \begin{vmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_7 \end{vmatrix}, \quad (8.26)$$

$$\bar{u}_2 = \begin{vmatrix} \cos^2 u_\kappa \\ \cos u_\kappa \sin u_\kappa \\ \sin^2 u_\kappa \end{vmatrix}, \quad \bar{u}_3 = \begin{vmatrix} \cos^3 u_\kappa \\ \cos^2 u_\kappa \sin u_\kappa \\ \cos u_\kappa \sin^2 u_\kappa \\ \sin^3 u_\kappa \end{vmatrix}. \tag{8.27}$$

The vectors $\bar{\alpha}, \bar{\beta}, \bar{\gamma}$ may now be represented in the form [31]

$$\bar{\alpha} = D_1 \bar{u}_1 \Delta_\kappa^4; \quad \bar{\beta} = D_2 \bar{u}_2 \Delta_\kappa^3; \quad \bar{\gamma} = D_3 \bar{u}_3 \Delta_\kappa^4; \quad \beta_6 = \Delta_\kappa^3, \tag{8.28}$$

where the matrices D_1 and D_2 may be derived from the elements of the matrix D_1 [31]:

$$D_2 = \begin{vmatrix} d_{11} & 2d_{11}d_{12} & d_{12}^2 \\ d_{21} & 2d_{21}d_{22} & d_{22}^2 \\ d_{11}d_{21} & d_{11}d_{22} + d_{12}d_{21} & d_{12}d_{22} \\ d_{31}d_{21} & d_{31}d_{22} + d_{32}d_{21} & d_{32}d_{22} \\ d_{11}d_{31} & d_{12}d_{31} + d_{11}d_{32} & d_{12}d_{32} \end{vmatrix}, \tag{8.29}$$

$$D_3 = \begin{vmatrix} d_{11} & 3d_{11}^2 d_{12} & 3d_{11}d_{12}^2 & d_{12}^3 \\ d_{21} & 3d_{21}^2 d_{22} & 3d_{21}d_{22}^2 & d_{22}^3 \\ d_{11}^2 d_{21} & d_{22}d_{11}^2 + 2d_{11}d_{21}d_{12} & d_{21}d_{12}^2 + 2d_{11}d_{12}d_{22} & d_{12}^2 d_{22} \\ d_{11}^2 d_{31} & d_{32}d_{11}^2 + 2d_{11}d_{31}d_{12} & d_{31}d_{12}^2 + 2d_{11}d_{12}d_{32} & d_{12}^2 d_{32} \\ d_{21}^2 d_{31} & d_{32}d_{21}^2 + 2d_{21}d_{31}d_{22} & d_{31}d_{22}^2 + 2d_{21}d_{22}d_{32} & d_{22}^2 d_{32} \\ d_{21}d_{11} & d_{12}d_{21}^2 + 2d_{11}d_{21}d_{22} & d_{11}d_{22}^2 + 2d_{12}d_{21}d_{22} & d_{12}d_{22}^2 \\ d_{11}d_{21}d_{31} & \begin{matrix} d_{11}d_{21}d_{32} + d_{11}d_{22}d_{31} + \\ + d_{12}d_{21}d_{31} \end{matrix} & \begin{matrix} d_{11}d_{22}d_{32} + d_{12}d_{21}d_{32} + \\ + d_{12}d_{22}d_{31} \end{matrix} & d_{12}d_{22}d_{32} \end{vmatrix}. \tag{8.30}$$

The values $\frac{d\beta_j}{dt}$, which are input into (4.71), are calculated according to the formulae

$$\frac{d\beta}{dt} = \begin{vmatrix} \frac{d\beta_1}{dt} \\ \vdots \\ \frac{d\beta_5}{dt} \end{vmatrix} = D_2 \frac{d}{dt} (\bar{u}_2 \Delta_\kappa^3) = D_2 b_\kappa \Delta_\kappa^2 \frac{d}{du_\kappa} (u_2 \Delta_\kappa^3), \tag{8.31}$$

$$\frac{d\beta_6}{dt} = -3e_\kappa b_\kappa \Delta_\kappa^4 \sin (u_\kappa - \omega_\kappa).$$

The vector's components $\frac{d}{du_{\text{к}}}(u_2\Delta_{\text{к}}^3)$ are equal to

$$\frac{d}{du_{\text{к}}}(\bar{u}_2\Delta_{\text{к}}^3)=\begin{vmatrix} -2\Delta_{\text{к}}^3\cos u_{\text{к}}\sin u_{\text{к}}-3e_{\text{к}}\Delta_{\text{к}}^2\sin(u_{\text{к}}-\omega_{\text{к}})\cos^2 u_{\text{к}} \\ \Delta_{\text{к}}^3\cos^2 u_{\text{к}}-3e_{\text{к}}\Delta_{\text{к}}^2\sin(u_{\text{к}}-\omega_{\text{к}})\cos u_{\text{к}}\sin u_{\text{к}} \\ 2\Delta_{\text{к}}^3\cos u_{\text{к}}\sin u_{\text{к}}-3e_{\text{к}}\Delta_{\text{к}}^2\sin(u_{\text{к}}-\omega_{\text{к}})\sin^2 u_{\text{к}} \end{vmatrix}. \quad (8.32)$$

Analysis of the ratios (4.40) - (4.42) and (8.21) - (8.32) shows that the evolutions of the KA's orbital elements depend to a significant degree on the relative positioning of the satellite orbits within the system in space and the external bodies. Consequently, over a long period of a system's existence the disruption of its initial structure is possible as a consequence of the various orientations of the respective perturbing bodies.

The cosine of the angle between the orbital plane of a j-th satellite system and the plane of the ecliptic is determined by the function

$$\cos(\Delta\varkappa_{\text{KA.C}})_j=\sin i_j\sin\varepsilon_0\cos\Omega_j+\cos i_j\cos\varepsilon_0, \quad (8.33)$$

where ε_0 is the angle between the equatorial plane and the plane of the ecliptic; and i_j, Ω_j are the orientation angles of the orbital plane of a j-th satellite in an inertial coordiante system.

The cosine of the angle between the orbital plane of a j-th satellite system and the orbital plane of the moon in turn is determined by the function

$$\cos(\Delta\varkappa_{\text{KA.Л}})_j=\sin i_j\sin i_{\text{Л.Э}}\cos(\Omega_j-\Omega_{\text{Л.Э}})+\cos i_j\cos i_{\text{Л.Э}}, \quad (8.34)$$

where $i_{\text{Л.Э}}$ is the orbital inclination of the moon relative to the equatorial plane of the earth and $\Omega_{\text{Л.Э}}$ is the longitude of the ascending node of the lunar orbit in the plane of the earth's equator.

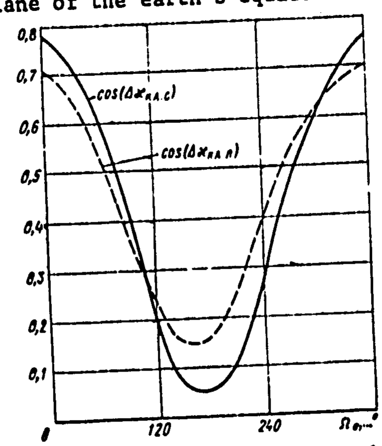

Figure 8.3. Characteristics of Directed Cosines

The function $i_{Л,э}$ is determined by the expression

$$\cos i_{Л,э} = \cos i_Л \cos \varepsilon_Л - \sin i_Л \sin \varepsilon_Л \cos \Omega_Л, \qquad (8.35)$$

and the function $\Omega_{Л,э}$, in turn, is from the equations

$$\left.\begin{aligned} &\sin i_{Л,э} \sin \Omega_{Л,э} = \sin i_Л \sin \Omega_Л; \\ &\sin i_{Л,э} \cos \Omega_{Л,э} = \cos i_Л \sin \varepsilon_э + \sin i_Л \cos \varepsilon_Л \cos \Omega_Л, \end{aligned}\right\} \qquad (8.36)$$

where $i_Л \approx 5{,}1°$ is the inclination of the moon to the plane of the ecliptic; and $\Omega_Л$ is the longitude of the ascending node of the moon's orbit relative to the point of the vernal equinox in the plane of the ecliptic. The function $\Omega_Л$ with sufficient accuracy for practical equations may be calculated according to the formula

$$\Omega^Л = 259°10'59'',79 - 1934°08'31'',23\ T_э, \qquad (8.37)$$

where $T_э$ is calculated wtih respect to the function which was presented in chapter 4.

In figure 8.3 there are presented for illustration functions of directed cosines $\cos(\Delta\varkappa_{A,Л})$, $\cos(\Delta\varkappa_{KA,C})$ in the function of the longitude of ascending node of the orbit under a fixed value for the initial inclination.

8.4 Orbital Construction of Satellite Systems

The orbital construction of SS is totally determined by the values of the parameters $a_j^0, e_j^0, i_j^0, \omega_{\pi j}^0, L_j^0, \Omega_j^0$ of each KA. Everywhere in the future we shall propose that we distribute by some type of integration algorithm for differential equations the motion of a KA (see chapter 4) and thus we can calculate the value of the functions $a_j(Э_j^0, t), \ldots, \Omega_j(Э_j^0, t)$ at any moment in time t.

We shall transpose the expression (8.3) for the function of the target, while using the following designations:

$$F_{j,j+1} = \sum_{n=1}^{\bar{n}} \max(0,\ t^n_{\text{н}j+1} - t^n_{\text{к}j}),\ j = 1, 2, \ldots, \bar{j} - 1; \qquad (8.38)$$

$$F_{\bar{j},1} = \sum_{n=1}^{\bar{n}} \max(0,\ t^{n+1}_{\text{н}1} - t^n_{\text{к}\bar{j}}). \qquad (8.39)$$

Then, it is apparent that

$$H = \sum_{j=1}^{\bar{j}-1} F_{j,j+1} + F_{\bar{j},1}$$

or, if one is introduce into the examination $(\bar{J}+1)$-й a hypothetical KA with the parameters

$$a^0_{\bar{J}+1}=a^0_1,\ e^0_{\bar{J}+1}=e^0_1,\ldots,\ L^0_{\bar{J}+1}=L^0_1,\ \Omega^0_{\bar{J}+1}=\Omega^0_1+2\pi, \tag{8.40}$$

then finally we derive

$$H=\sum_{j=1}^{\bar{J}} F_{j,j+1}. \tag{8.41}$$

It is clear that the functions $F_{j,j+1}$ depend only on the parameters of a j-th (j+1)-th KA, that is

$$F_{j,j+1}=F_{j,j+1}(a^0_1,\ e^0_j,\ldots,\ \Omega^0_j,\ a^0_{j+1},\ e^0_{j+1},\ldots,\ \Omega^0_{j+1}).$$

Determination of the values for these functions is based on the expressions (8.38), (8.39) and (8.40), as well as the values for the functions

$$a_j(\vartheta^0_j,\ t),\ e_j(\vartheta^0_j,\ t),\ldots,\Omega_j(\vartheta^0_j,\ t),\ t_{\text{н}j}(\vartheta_j) \text{ и } t_{\text{к}j}(\vartheta_j).$$

Under these conditions the task of orbital construction takes on the form

$$H=\sum_{j=1}^{\bar{J}} F_{j,j+1}\Rightarrow\min$$

under the limitations

$$a^{0*}_j\leqslant a^0_j\leqslant a^{0**}_j,\ a^0_{\bar{J}+1}=a^0_1; \tag{8.42}$$

. . . .

$$L^{0*}_j\leqslant L^0_j\leqslant L^{0**}_j,\ L^0_{\bar{J}+1}=L^0_1; \tag{8.43}$$

$$\Omega^{0*}_j\leqslant \Omega^0_j\leqslant \Omega^{0**}_j,\ \Omega^0_{\bar{J}+1}=\Omega^0_1+2\pi. \tag{8.44}$$

In this case it is proposed that the remaining forms o. restriction which have gone into determining the numbers $A_э$ (see 8.6), and are taken into account in the construction of the work zone.

To resolve this task we shall make use of a combination of two methods: a partial improvement of group variables [14] and dynamic programming [6]. The first method represents an integration procedure, at each step of which there is a successive minimization (for example, by the method of dynamic programming) of the target's function (8.41) along the variables $\Omega^0{}_j, j=1, 2, \ldots, \bar{J}$, through the restrictions (8.44) and through the fixed values of the remaining variables, along the variables $a_j, j=1, 2, \ldots, \bar{J}$, through the restrictions (8.42), etc., along the variables $L_j{}^0, j=1, 2, \ldots, \bar{J}$, through the restrictions (8.43), following which the process is repeated again. It is known that if the function H is differentiated, then the process coincides with the minimum (local or global, dependent on the properties of the curvature of H). Inasmuch as the restrictions (8.42) - (8.43) are of the same type, it is sufficient for us to set forth the method of dynamic programming for minimization of (8.41) under the restrictions (8.42) and (8.44).

Thus, while fixing all of the variables, aside from $\Omega_j^0,\ j=1,2,\dots,\bar{j}$, we have the task

$$H(\Omega_1^0, \Omega_2^0, \dots, \Omega_{\bar{j}}^0) = \sum_{j=1}^{\bar{j}} F_{j,j+1}(\Omega_j^0, \Omega_{j+1}^0) \to \min; \quad (8.45)$$

$$\Omega_1^0 < \Omega_2^0 < \dots < \Omega_{\bar{j}+1}^0;$$

$$\Omega_{\bar{j}+1}^0 = \Omega_1^0 + 2\pi.$$

Let

$$P_N(\Omega_1^0, \Omega_N^0) = \min \sum_{j=1}^{N-1} F_{j,j+1}(\Omega_j^0, \Omega_{j+1}^0),$$

$N \geqslant 2$ is the value of the target's function which corresponds to the optimum disposition N of the KA under the condtion where the position of the first Ω_1^0 and N-th (Ω_N^0) of the KA are fixed. Then, on the strength of Bellman's principle of optimization the following recurrence ratios are correct

$$\left.\begin{aligned} &P_2(\Omega_1^0, \Omega_2^0) = F_{1,2}(\Omega_1^0, \Omega_2^0),\ 0 \leqslant \Omega_1^0 \leqslant \Omega_2^0 < 2\pi, \\ &P_N(\Omega_1^0, \Omega_N^0) = \min_{0 \leqslant \Omega_1^0 < \Omega_{N-1}^0 < \Omega_N^0} [P_{N-1}(\Omega_1^0, \Omega_{N-1}^0) + \\ &+ F_{N-1,N}(\Omega_{N-1}^0, \Omega_N^0)],\ N = 3, 4, \dots, \bar{j}+1, \end{aligned}\right\} \quad (8.46)$$

$$\text{где } \Omega_N^0 \begin{cases} < \Omega_1^0 + 2\pi \text{ при } N \leqslant \bar{j}, \\ = \Omega_1^0 + 2\pi \text{ при } N = \bar{j}+1. \end{cases}$$

From (8.46) it follows that the solution of the task (8.45) in the final analysis leads to the construction and minimization of the function of a single variable

$$P_{\bar{j}+1}(\Omega_1^0, \Omega_1^0 + 2\pi) \text{ по } \Omega_1^0 \in [0, 2\pi].$$

The method of minimization (8.41) under the restriction (8.43) depends little on that presented. The corresponding recurrent ratios have the form*

*The realization of the ratios (8.46) and (8.47) within the bounds of the method for partial improvement of group variables for all six parameters requires a large expenditure of machine time. However, when examining each concrete system (see section 8.3) there often exists the possibility

$$P_2(L_1^0, L_2^0) = F_{1,2}(L_1^0, L_2^0), \quad L_1^{0*} \leqslant L_1^0 \leqslant L_1^{0**};$$
$$L_2^{0*} \leqslant L_2^0 \leqslant L_2^{0**};$$
$$P_N(L_1^0, L_N^0) = \min_{L_{N-1}^{0*} \leqslant L_{N-1}^0 \leqslant L_{N-1}^{0**}} [P_{N-1}(L_1^0, L_{N-1}^0) + \tag{8.47}$$
$$+ F_{N-1,N}(L_{N-1}^0, L_N^0)], \quad N = 3, 4, \ldots, \bar{j}+1.$$

The solution is performed by means of a minimization function

$$P_{\bar{j}+1}(L_1^0, L_1^0) \text{ по } \dot{L}_1^0 \in [L_1^{0*}, L_1^{0**}].$$

A general block diagram of the combined method for resolving the problem of orbital construction is presented in figure 8.4.

The given diagram features a specific universality in the sense that through its use one may encompass the broadest number of orbital construction problems which allow for the calculation, according to the wishes of the researcher, of the influence of system deformation, correction strategy, compensation, "light exposures" of the KA equipment by the sun, etc.

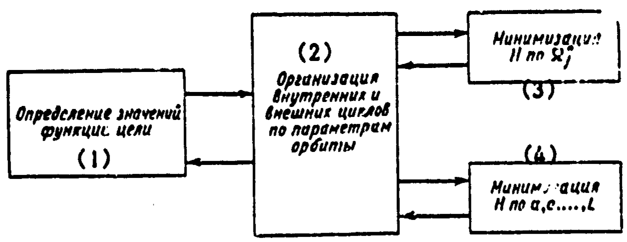

Figure 8.4. Block Diagram of the Combined Method for Solving an Orbital Construction Problem

Key:
1. Determining the values for the target's function
2. Organization of internal and external cycles according to the orbit's parameters
3. Minimization of H according to Ω_j
4. Minimization of H according to a, e, ..., L

[continued from previous page] to be limited by one, two or a maximum of three groups of variables. Under these conditions the proposed procedure becomes totally realized, and moreover, the apparent generalization for the ratios (8.46) and (8.47) in the case of two (technically more complex than three) groups of parametes allows one to derive a precise solution.

As an example, we shall examine the problem of orbital construction of an SS intended to provide uninterrupted communications between Moscow and Washington. As is known [21,53], in this system KA of the "Molniya" type are used with an inclination of 64^0, an eccentricity of 0.74 and an orbital period equal to one half a stellar day. For an orbit of this type the RZ duration during which communications may be accomplished simultaneously amounts to slightly over eight hours. At a minimum, three KA are necessary to provide round-the-clock uninterrupted communications.

The solution to this problem was accomplished under the following suppositions: 1) the SS consists of three similar KA; 2) the evolution of the longitude of ascending node Ω over a year's interval is a function of the initial value Ω^0 and varies linearly, that is $\Omega^n = \Omega^0 + \Delta\Omega n$, where $\Delta\Omega$ is the increment for a single day, $\Delta\Omega = \Delta\Omega(\Omega^n)$; n is the current day; 3) the parameters of the KA $(a_j, e_j, i_j, \omega_j, t_j, j=1, 2, 3)$ system are constant; and 4) the duration of the work zone for each KA for all n amounts to eight hours.

In figure 8.5 the function is presented for the minimum total time interval duration, free of servicing -- $P_4(\Omega_1^0, \Omega_1^0+2\pi)$ from Ω_1^0 is the initial longitude of the ascending node for the first KA.

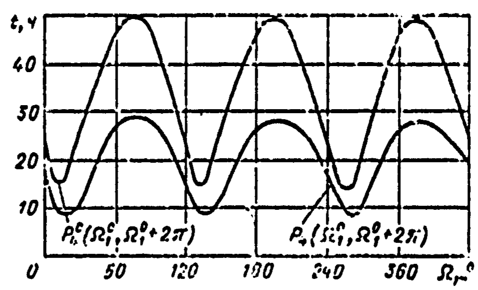

Figure 8.5. Optimum Constancy Curves

Analysis of the results shows that $P_4(\Omega_1^0, \Omega_1^0+2\pi)$ significantly depends on the value Ω_1^0. Thus, the global minimum is achieved in the region $\Omega_1^0 = 15^0$. Therefore, the total observation time losses amount to ~6.5 hours, which is also four times less than the losses characteristic when $\Omega_1^0 = 70^0$.

For comparison, on this same chart, there is presented the function of losses under a strictly symmetrical initial construction of the KA network $P_4^c(\Omega_1^0, \Omega_1^0+2\pi)$.

8.5 Construction of an Ideal Correction Rule

We shall examine the task of constructing an ideal correction rule having renounced the proposition of limited reserves of "energy" on board the KA. If the correction schematic is fixed, and the magnitude of the correction impulse is restricted, then by means of the methods presented in [2], one may determine for each given set of orbital element values a, e, ..., Ω, the region of realized element values

$$A_{\mathfrak{s}} = [a^{*}, a^{**}] \times [e^{*}, e^{**}] \times \ldots \times [\Omega^{*}, \Omega^{**}],$$

where «x» is the sign of the cartesian product. It is natural that

$$a^{*} = a^{*}(a, e, \ldots, \Omega);\ a^{**} = a^{**}(a, e, \ldots, \Omega), \tag{8.48}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

and everywhere in the future we shall assume the functions (8.48) are known. In these hypotheses the problem of an ideal correction leads to the minimization function

$$H(\bar{\mathfrak{Z}}_1^1, \ldots, \bar{\mathfrak{Z}}_{\bar{j}}^1, \ldots, \bar{\mathfrak{Z}}_1^{\bar{n}}, \ldots, \bar{\mathfrak{Z}}_{\bar{j}}^{\bar{n}}) \tag{8.49}$$

under the restrictions

$$\bar{\mathfrak{Z}}_j^n \in A^n_{\mathfrak{Z}j},\ j = 1, 2, \ldots, \bar{j},\ n = 1, 2, \ldots, \bar{n},$$

where $\bar{\mathfrak{Z}}_j^n$ is the vector of the orbital elements of the j-th KA on the n-th VTs following the correction.

We shall comment on this formulation. Just as the initial orbital construction is given according to the hypothesis, so one may forecast the movement of the SS over an interval of time which corresponds to the initial time cycle and derives the vector $\mathfrak{Z}_j^1, j = 1, 2, \ldots, \bar{j}$.

According to these values it is possible to construct the areas $A^1_{\mathfrak{Z}j}$ and through the solution of the problem (8.49) for n=1 one can find the vector $\bar{\mathfrak{Z}}_j^1, j = 1, 2, \ldots, \bar{j}$. Treating the derived elements as being initial, one may determine the vector $\mathfrak{Z}_j^2, j = 1, 2, \ldots, \bar{j}$, through a method similar to the one described above, and predict the SS motion over the second time cycle. Further constructing the areas $A^2_{\mathfrak{Z}j}$ and, having resolved the problem (8.48) for n=2, we derive the vector $\bar{\mathfrak{Z}}_j^2$. The process is continued in a manner similar for n=3, 4, ..., and $\bar{n}$. In this manner, the problem (8.49) may be approximately summarized into a sequence of tasks of orbital construction examined over separate time cycles*. Consequently, for their solution the already well known solution procedure may be used.

The derived sequence $\mathfrak{Z}_j^1 - \bar{\mathfrak{Z}}_j^1, \mathfrak{Z}_j^2 - \bar{\mathfrak{Z}}_j^2, \ldots, \mathfrak{Z}_j^{\bar{n}} - \bar{\mathfrak{Z}}_j^{\bar{n}}$ determines the desired strategy for correcting the motion parameters of a j-th KA.

According to that presented in section 8.4, the given method for constructing an ideal correction is too time consuming, and therefore we shall examine a significantly more efficient resolving procedure which is applicable in a number of supplementary hypotheses (in many cases which are

*More precisely, of time periods which (see below) do not correspond with time cycles.

being performed in practice):

the duration of the work zone

$$t_{\text{к}j}^{n}(\mathcal{Э}_j^n) - t_{\text{н}j}^{n}(\mathcal{Э}_j^n) = d_j^n \tag{8.50}$$

is kept unchanged following the performance of the correction on a given orbit;

for each pair of n and j the allowable range $[t_{\text{н}j}^{n*}, t_{\text{н}j}^{n**}]$ for change in the value of $t_{\text{н}j}$ (this range may not even take into account the restriction of the correlated impulse) is known, and in other words, the following functions are known

$$t_{\text{н}}^{*}(\mathcal{Э}) \text{ и } t_{\text{н}}^{**}(\mathcal{Э}).$$

In these hypotheses the problem of an ideal correction amounts to determining the values $t_{\text{н}j}^n$, $n=1, 2, \ldots, \bar{n}$, $j=1, 2, \ldots, \bar{j}$, which have minimized the function

$$\begin{aligned} H = &\left[f(t_{\text{н}1}^1, t_{\text{н}2}^1) + f(t_{\text{н}2}^1, t_{\text{н}3}^1) + \ldots + f(t_{\text{н}\bar{j}}^1, t_{\text{н}1}^2) + f(t_{\text{н}1}^2, t_{\text{н}2}^2)\right] + \\ &+ \left[f(t_{\text{н}2}^2, t_{\text{н}3}^2) + \ldots + f(t_{\text{н}\bar{j}}^2, t_{\text{н}1}^3) + f(t_{\text{н}1}^3, t_{\text{н}2}^3) + f(t_{\text{н}2}^3, t_{\text{н}3}^3)\right] + \ldots \\ &+ \left[\ldots + f\left(t_{\text{н}\bar{j}}^{\bar{n}}, t_{\text{н}1}^{\bar{n}+1}\right)\right] \end{aligned} \tag{8.51}$$

under the restrictions

$$t_{\text{н}j}^{n*} \leqslant t_{\text{н}j}^n \leqslant t_{\text{н}j}^{n**}, \; j=1, 2, \ldots, \bar{j}, \tag{8.52}$$

where

$$t_{\text{н}1}^1 = a, \; t_{\text{н}1}^{\bar{n}+1} = b, \; f(t_{\text{н}j}^n, t_{\text{н}j+1}^n) = \max(0, t_{\text{н}j+1}^n - t_{\text{н}j}^n - d_j^n).$$

The diagram for resolving the problem (8.51) and (8.52) is essentially similar to the diagram for resolving the problem (8.49). It also includes a sequence of stages (which do not correspond to the time cycles), on each of which the truncated task (8.51) - (8.52) is resolved.

At the first stage we derive

$$\begin{gathered} f(t_{\text{н}1}^1, t_{\text{н}2}^1) + f(t_{\text{н}2}^1, t_{\text{н}3}^1) + \ldots + f(t_{\text{н}\bar{j}}^1, t_{\text{н}1}^2) + f(t_{\text{н}1}^2, t_{\text{н}2}^2) \to \min; \\ t_{\text{н}j}^{1*} \leqslant t_{\text{н}j}^1 \leqslant t_{\text{н}j}^{1**}, \; t_{\text{н}2}^2 = t_{\text{н}2}^1 + \Delta^1, \; j=1, 2, \ldots, \bar{j}, \end{gathered} \tag{8.53}$$

where Δ^1 is a constant which is determined by the forecast.

As a result of its solution, we derive certain values $\bar{t}_{\text{н}j}^1$, $j=1, 2, \ldots, \bar{j}$, through which the values of the orbital elements which have been determined by corresponding ratios

$$\begin{gathered} t_{\text{н}1}^{2*} \leqslant t_{\text{н}1}^2 \leqslant t_{\text{н}}^{2**}. \\ t_{\text{н}j}^1(\bar{a}_j^1, \bar{c}_j^1, \ldots, \bar{\Omega}_j^1) = \bar{t}_{\text{н}j}^1, \; j=1, 2, \ldots, \bar{j}. \end{gathered} \tag{8.54}$$

If the correction is uniparametric, then the corrected value of the corresponding element is calculated unambiguously and in the opposite case we have a single equation with k unknowns where k>1. Their selection may conform to the supplementary conditions which are refined by the correction schematic.

The derived values of the elements $\bar{a}_j^1, \bar{c}_j^1, \ldots, \bar{\Omega}_j^1$ facilitate prediction at the second stage, determination of t_{Hj}^{2} and t_{Hj}^{2**} and the resolution of the problem of an ideal correction at this stage:

$$f(t_{H2}^2, t_{H3}^2) + \ldots + f(t_{H\bar{J}}^2, t_{H1}^3) + f(t_{H1}^3, t_{H2}^3) + f(t_{H2}^3, t_{H3}^3) \Rightarrow \min;$$

$$t_{Hj}^{2*} \leqslant t_{Hj}^2 \leqslant t_{Hj}^{2**}, \ j = 1, 2, \ldots, \bar{J}, \ t_{Hj}^{3*} \leqslant t_{Hj}^3 \leqslant t_{Hj}^{3**}, j = 1, 2, \ldots \quad (8.55)$$

$$t_{H3}^3 = t_{H3}^2 + \Delta^2,$$

etc. In this manner, the task of an ideal correction is resolved subsequently for each stage. The correction strategy is constructed in a manner similar to that depicted above.

There remains for us an examination of the methodology for solving the problems of the type described in (8.53), (8.55), etc.

$$\sum_{j=0}^{\bar{J}} f(x_j, x_{j+1}) \Rightarrow \min; \quad (8.56)$$

$$a_j \leqslant x_j \leqslant b_j, \ x_{\bar{J}+1} = x_1 + \Delta, \ j = 1, 2, \ldots, \bar{J},$$

where x_0 is fixed,

$$f(x_j, x_{j+1}) = \max(0, x_{j+1} - x_j + d_j).$$

The sense of the new designators is apparent.

To solve the problem (8.56) we again make use of the recurrence ratios of dynamic programming resting the process of their transformation on the following sufficiently general statements.

Let the linear functions $f_i(x) = a_i x + b_i, a_i \neq 0, i = 1, 2, \ldots, \bar{I}$ be such that

$$a_i b_j - b_i a_j \leqslant c(a_i - a_j) \quad (8.57)$$

for all pairs of i and j which satisfy the condition

$$j \in J_1 = \{i : a_i < 0\}, \ i \in J_2 = \{i : a_i > 0\}, \quad (8.58)$$

where c>0 is a certain constant. Then for any final segment [a,b] the following equation holds true

$$\min_{x \in [a,b]} \max\{f_i(x), c\} = \max\{\min_{x \in [a,b]} f_i(x), c\}. \quad (8.59)$$

Proof.

Let $x_i' = \frac{c - b_i}{a_i}$ (8.60)

is the radical of the equation $a_i x + b_i = c$. We shall introduce into the examination the values

$$\alpha = \max_{i \in J_1} x_i' = x_{i'}' \text{ и } \beta = \min_{i \in J_2} x_i' = x_{i''}'. \tag{8.61}$$

We shall show that $\alpha \leqslant \beta$.
Having proposed the opposite, we will derive an agreement (8.60) and (8.61),

$$\frac{c - b_{i''}}{a_{i''}} < \frac{c - b_{i'}}{a_{i'}}$$

or, taking into account the fact that $a_{i''} > 0$, а $a_{i'} < 0$,

$$a_{i'} b_{i''} - a_{i''} b_{i'} > c(a_{i'} - a_{i''}),$$

which contradicts (8.57).

Thus, it is argued that under the condition (8.57) the function $\Phi(x) = \max\{f_i(x), c\}$ features a portion of the constancy which is restricted by the points α и β, $\alpha \leqslant \beta$, on which a value equal to c is received. It is known that this function bulges down (concave), and consequently, to the "right" of the point β $\Phi(x)$ grow monotonically, and "to the left" of the point α decays monotonically.

We shall examine two cases

1. $[a, b] \cap [\alpha, \beta] \neq \varnothing$. (8.62)

In this case, it is apparent, that $\min_{x \in [a,b]} \max\{f_i(x), c\} = c$ is also achieved at any point $x \in [a, b] \cap [\alpha, \beta]$.

We shall examine a random point $\bar{x} \in [a, b] \cap [\alpha, \beta]$. Thus, $\bar{x} \leqslant \beta \leqslant x_i'$ (see 8.61) for all $i \in J_2$, so that for these functions

$$f_i(\bar{x}) \leqslant f_i(x_i') = c. \tag{8.63}$$

On the other hand, since $\bar{x} \geqslant \alpha \geqslant x_i'$ for all $i \in J_1$, then for these functions the condition (8.63) is also true. Consequently,

$$\min_{x \in [a,b]} f_i(x) = \min_{x \in [a,b] \cap [\alpha,\beta]} f_i(x) \leqslant f_i(\bar{x}) \leqslant c$$

and $\max\{\min_{x \in [a,b]} f_i(x), c\} = c$, which also needs to be proved.

2. $[a, b] \cap [\alpha, \beta] = \varnothing$.

Assume that α>β is for a determinant. Thus the function Φ (x) is "right" of the point β which is growing monotonically so that

$$\min_{x\in[a,b]}\max\{f_i(x),\ c\}=\max\{f_i(a),\ c\}=\max\{\max_{i\in J_1}f_i(a),\ \max_{i\in J_2}f_i(a),\ c\}. \quad (8.64)$$

On the other hand,

$$\max\{\min_{x\in[a,b]}f(x),\ c\}=\max\{\max_{i\in J_2}f_i(a),\ \max_{i\in J_1}f_i(b),\ c\}, \quad (8.65)$$

inasmuch as the functions $f_i(x)$ are growing monotonically when $i\in J_2$ and decay monotonically when $i\in J_1$.

From the computation of α and β and the inequality $a<\beta<a$ it follows that

$$\max_{i\in J_1}f_i(a)<\max_{i\in J_1}f_i(\alpha)=c;\ \max_{i\in J_2}f_i(a)>\max_{i\in J_2}f_i(\beta)=c;$$
$$\max_{i\in J_1}f_i(b)<\max_{i\in J_2}f_i(a). \quad (8.66)$$

Analysis of the right portions of the equations (8.64) and (8.65) shows that on the strength of (8.66) their continuation gives the very same result which is:

$$\max_{i\in J_2}f_i(a),$$

which also completes the proof of the statement.

Remarks. If $a_i=-1$ under all $i\in J_1$ and $a_j=+1$ under all $j\in J_2$, then the condition (8.57) takes on the form

$$b_i+b_j\leqslant 2c. \quad (8.67)$$

Changing over to the method presented for the solution, we shall introduce the functions into our examination for

$$P_N(x_1,\ x_N)=\min_{a_j<x_j<b_j}\sum_{j=1}^{N-1}f(x_j,\ x_{j+1}),\ N\geqslant 2. \quad (8.68)$$

These functions satisfy the recurrence ratios which are similar to (8.47), that is

$$P_2(x_1,\ x_2)=f(x_1,\ x_2),\ a_1\leqslant x_1\leqslant b_1,\ a_2\leqslant x_2\leqslant b_2,$$
$$P_N(x_1,\ x_N)=\min_{a_{N-1}<x_{N-1}<b_{N-1}}[P_{N-1}(x_1,\ x_{N-1})+f(x_{N-1},\ x_N)],\ N\geqslant 3. \quad (8.69)$$

It turns out that the functions (8.69) may be calculated in an explicit form. Actually,

$$P_3(x_1,\ x_3)=\min_{a_2<x_2<b_2}\{\max(0,\ x_2-x_1+d_1)+\max(0,\ x_3-x_2+d_2)\}=$$
$$=\min_{a_2<x_2<b_2}\max(0,\ x_2-x_1+d_1,\ x_3-x_2+d_2,\ x_3-x_1+d_1+d_2). \quad (8.70)$$

We shall define

$$c \equiv \max(0,\ x_3 - x_1 + d_1 + d_2);$$
$$x_2 - x_1 + d_1 \equiv a_1 x_2 + b_1, \text{ где } a_1 = 1,\ b_1 = -x_1 + d_1;$$
$$x_3 - x_2 + d_2 \equiv a_2 x_2 + b_2, \text{ где } a_2 = -1;\ b_2 = x_3 + d_2$$

and we shall verify the practicability of the conditions (8.67). It is apparent that

$$b_1 + b_2 = x_3 - x_1 + d_1 + d_2 \leqslant \max(0,\ x_3 - x_1 + d_1 + d_2) = c \leqslant 2c,$$

that is we may make use of the equation (8.59).
Continuing the chain of equations (8.70), we derive

$$P_3(x_1,\ x_3) = \max(0,\ a_2 + d_1 - x_1,\ x_3 - b_2 + d_2; \quad (8.71)$$
$$x_3 - x_1 + d_1 + d_2) = \max(l_3,\ m_3,\ -x_1,\ x_3 + t_3,\ x_3 - x_1 + g_3),$$

where $l_3 = 0,\ m_3 = a_2 + d_1;\ t_3 = -b_2 + d_2,\ g_3 = d_1 + d_2.$

The number of values x_2 which are realized (8.70) is determined from the ratios

$$x_2 \begin{cases} \in [a_2,\ b_2] \cap [l^*,\ l^{**}], \text{ если } [a_2,\ b_2] \cap [l^*,\ l^{**}] \neq \varnothing \\ = b_2, \text{ если } b_2 < l^* \\ = a_2, \text{ если } a_2 > l^{**}, \end{cases} \quad (8.72)$$

where

$$l^* = x_3 + d_2 - \max(0,\ x_3 - x_1 + d_1 + d_2),$$
$$l^{**} = x_1 - d_2 + \max(0,\ x_3 - x_1 + d_1 + d_2)$$

are the segment's boundaries for the constant function from x_2:

$$\max(0,\ x_2 - x_1 + d_1,\ x_3 - x_2 + d_2,\ x_3 - x_1 + d_1 + d_2).$$

The validity of (8.72) follows directly from those discussions which accompanied the proof (8.59). In a similar manner one may derive the expressions for

$$P_4(x_1,\ x_4),\ P_5(x_1,\ x_5), \ldots,\ P_N(x_1,\ x_N), \ldots,\ P_{\bar{J}+1}(x_1,\ x_{\bar{J}+1}),$$

and in so doing it turns out that similarly (8.71)

$$P_{N-1}(x_1,\ x_{N-1}) = \max(l_{N-1},\ m_{N-1} - x_1,\ t_{N-1} + x_{N-1},\ x_{N-1} - x_1 + g_{N-1}); \quad (8.73)$$
$$P_N(x_1,\ x_N) = \max(l_N,\ m_N - x_1,\ t_N + x_N,\ x_N - x_1 + g_N)$$

for all $N = 3, 4, \ldots, \bar{J} + 1$, и

$$l_N = \max(l_{N-1},\ t_{N-1} - a_{N-1});$$
$$m_N = \max(m_{N-1},\ a_{N-1} + g_{N-1});$$
$$t_N = \max(-b_{N-1} + d_{N-1} + l_{N-1},\ d_{N-1} + t_{N-1}); \quad (8.74)$$
$$g_N = \max(-b_{N-1} + d_{N-1} + m_{N-1},\ d_{N-1} + g_{N-1}).$$

Actually, it agrees with (8.69)

$$
\begin{aligned}
P_N(x_1, x_N) &= \min_{a_{N-1}<x_{N-1}<b_{N-1}} [\max(0, x_N - x_{N-1} + d_{N-1}) + \\
&+ \max(l_{N-1}, m_{N-1} - x_1, t_{N-1} + x_{N-1}, x_{N-1} - x_1 + g_{N-1})] = \\
&= \min_{a_{N-1}<x_{N-1}<b_{N-1}} \max(l_{N-1}, m_{N-1} - x_1, t_{N-1} + x_{N-1}, x_{N-1} - x_1 + \\
&+ g_{N-1}, x_N - x_{N-1} + d_{N-1} + l_{N-1}, m_{N-1} - x_1 + x_N - x_{N-1} + d_{N-1}, \\
&t_N + x_N + d_{N-1}, x_N - x_1 + d_{N-1} + g_{N-1}).
\end{aligned} \tag{8.75}
$$

It is not difficult to verify the fulfillment of the conditions (8.67). Consequently,

$$
\begin{aligned}
P_N(x_1, x_N) &= \max(l_{N-1}, m_{N-1} - x_1, t_{N-1} + a_{N-1}, a_{N-1} - x_1 + g_{N-1}, \\
&x_N - b_N + d_{N-1} + l_{N-1}, m_{N-1} - x_1 + x_N + d_{N-1} - b_{N-1}, \\
&x_N + t_{N-1} + d_{N-1}, x_N - x_1 + d_{N-1} + g_{N-1}) = \\
&= \max(l_N, m_N - x_1, t_N + x_N, x_N - x_1 + g_N),
\end{aligned}
$$

where l_N, m_N, t_N, g_N are determined by the formulae (8.74).

The number of values x_{n-1}, which are realized by (8.75), is determined from the ratios

$$
x_{N-1} \begin{cases} \in [a_{N-1}, b_{N-1}] \cap [l^*, l^{**}], \text{ если } [a_{N-1}, b_{N-1}] \cap [l^*, l^{**}] \neq \emptyset \\ = b_{N-1} \text{ при } b_{N-1} < l^*; \\ = a_{N-1} \text{ при } a_{N-1} > l^{**}, \end{cases} \tag{8.76}
$$

where

$$
\begin{gathered}
l^* = \max(x_N + d_{N-1} + l_{N-1}, m_{N-1} - x_1 + x_N + d_{N-1}) - \varphi; \\
l^{**} = \varphi - \max(l_{N-1}, g_{N-1} + x_1), \\
\varphi = \max(l_{N-1}, m_{N-1} - x_1, t_{N-1} + x_N + d_{N-1}, x_N - x_1 + d_{N-1} + g_{N-1}).
\end{gathered}
$$

The solution of the problem (8.56) is complete through the minimization of the function of a single variable $x_1 \in [a_1, b_1]$:

$$
\begin{aligned}
\Phi(x_1) &= \max(0, x_1 - x_0 + d_0) + P_{j+1}(x_1, x_1 + \Delta) = \\
&= \max(0, x_1 - x_0 + d_0) + \max(l_{\bar{J}+1}, m_{\bar{J}+1} - x_1, t_{j+1} + x_1 + \Delta, \Delta + g_{\bar{J}+1}).
\end{aligned} \tag{8.77}
$$

We will not remain at length on the problem of minimization $\Phi(x_1)$, noting that the function $\Phi(x_1)$ is constant piecewise, bulging beneath and determining its minimum distance is not difficult.

8.6. Constuction of an Actual Correction Rule

As a result of the solution to the problem for constructing an ideal correction rule we derive for each j-th KA the vector-function $\hat{\mathcal{E}}_j(\mathcal{E}_{0j}, t)$ in the hypothesis with an unlimited reserve of "energy" on board the KA and, perhaps, the values of the correction impulse. The construction of a real correction rule is already accomplished for each KA system in isolation, taking into account the restriction of "energy" reserves and the magnitude of the correction impulse. If we are to define the orbital elements for the j-th KA which correspond to the real correction rule $\Delta V_j(t)$, through $\mathcal{E}_j(\mathcal{E}_{0j}, \Delta V_j(t), t)$, then the problem being examined in a discrete statement leads to a determination of the series* ΔV^n, which satisfies the conditions

$$\Delta V^n \in U, \; n=0, \; 1, \ldots, \; \bar{n}-1; \tag{8.78}$$

$$\sum_{n=0}^{\bar{n}-1} |\Delta V^n| \leqslant V \tag{8.79}$$

and which realizes the minimum square distance between the rules and the motion

$$\rho^2_{a,b}(\hat{\mathcal{E}}(\mathcal{E}_0, n), \mathcal{E}(\mathcal{E}_0, \Delta V^n, n))$$

or by means of the work zones

$$\sum_{n=0}^{\bar{n}} \rho^2([\hat{t}^n_{н}, \hat{t}^n_{к}], [t^n_{н}, t^n_{к}]). \tag{8.80}$$

Here U is an acceptable number for the values of correcting impulses; and V is the "energy" reserve.
As before we shall consider the functions $t^n_{н}(\mathcal{E})$ и $t^n_{к}(\mathcal{E})$ as being known.
We shall propose a model for the motion of the KA in the form

$$\mathcal{E}^{n+1}=f(\mathcal{E}^n, \; \Delta V^n, \; n), \; n=0, \; 1, \ldots, \; \bar{n}-1, \; \mathcal{E}^0 \tag{8.81}$$

where the function f characterizes the prediction for the motion of the KA for a revolution. We shall transform the restriction (8.79), while introducing a new variable into the examination

$$V^n=\sum_{\kappa=0}^{n-1} |\Delta V^\kappa|,$$

then we derive

$$V^{n+1}=V^n+|\Delta V^n|, \tag{8.82}$$

whereupon $V^n \leqslant V.$ (8.83)

*The index j further subsides.

It is totally clear that the ratios (8.81) and (8.82) may be written in a single form if we are to add the vector Э^{n+1} of still another component V^{n+1} and designate $\| \text{Э}^{n+1}, V^{n+1} \|^{T} = \bar{\text{Э}}^{n+1}$. In the general case the vector $\bar{\text{Э}}^{n+1}$ is seven-dimensional: $\bar{\text{Э}}^{n+1} = \| \text{Э}_1^{n+1}, \text{Э}_2^{n+1}, \ldots, \text{Э}_7^{n+1} \|^{T}$. Finally, assuming

$$\bar{f}_l(\bar{\text{Э}}^n, n) = \begin{cases} f_l(\text{Э}^n, \Delta V^n, n), & l = 1, 2, \ldots, 6, \\ \text{Э}_7^n + |\Delta V^n| & \text{при } l = 7, \end{cases}$$

instead of (8.81) we finally derive

$$\bar{\text{Э}}^{n+1} = \bar{f}(\bar{\text{Э}}^n, n), \quad \bar{\text{Э}}_7^{\bar{n}} \leqslant V, \tag{8.84}$$

where $\bar{f} = \| f_1, f_2, \ldots, f_7 \|^{T}$.

Defining further

$$\rho^2([\hat{t}_{н}^n, \hat{t}_{к}^n], [t_{н}^n, t_{к}^n]) = f_0(\hat{\text{Э}}^n, \bar{\text{Э}}^n, n).$$

In these designations the task for constructing a real correction rule takes on the form

$$\sum_n f_0(\hat{\text{Э}}^n, \bar{\text{Э}}^n, n) \Rightarrow \min \tag{8.85}$$

under the restrictions of (8.84).

The method for dynamic programming which is proposed for solving this task [6] leads to the following Bellman equations

$$B(m, \bar{\text{Э}}) = \min_{\substack{\Delta V \in U \\ \bar{f}(\bar{\text{Э}}, \Delta V, m) \in F(m+1)}} [f_0(\hat{\text{Э}}^m, \bar{\text{Э}}, m) + B(m+1, \bar{f}(\bar{\text{Э}}, m)], \tag{8.86}$$

where

$$B(m, \bar{\text{Э}}) = \min_{\substack{\Delta V^n \in U \\ \bar{\text{Э}}^m = \bar{\text{Э}}, \\ \text{Э}_7^{\bar{n}} < V, \\ n = m, m+1, \ldots, \bar{n}.}} \sum_{n=m}^{\bar{n}} f_0(\hat{\text{Э}}^n, \bar{\text{Э}}^n, n),$$

F(m) is the number of points $\bar{\text{Э}}$, from which the admissable trajectories $\bar{\text{Э}}^n$, $\bar{\text{Э}}^m = \bar{\text{Э}}$ fall within the region $\text{Э}_7^{\bar{n}} \leqslant V$, it is apparent,

$$F(\bar{n}) = \{\bar{\text{Э}}^n | \bar{\text{Э}}_7^{\bar{n}} \leqslant V\},$$

$$F(m) = \{\bar{\text{Э}}^m \mid f(\bar{\text{Э}}^m, m) \in F(m+1) \text{ under certain } \Delta V^m \in U\}.$$

The realization of the ratios (8.86) for a seven-dimensional vector of conditions $\bar{\text{Э}}$ is practically impossible, therefore some other kind of measures are normally used to reduce the dimension for the conditions of space while being limited to the derivation of an approximate solution. Most promising in this plan are the methods which employ Langrangian multipliers [6], as well as the methods based on a combination of ratios (8.86) and the method of partial improvement for variable groups (see section 8.4).

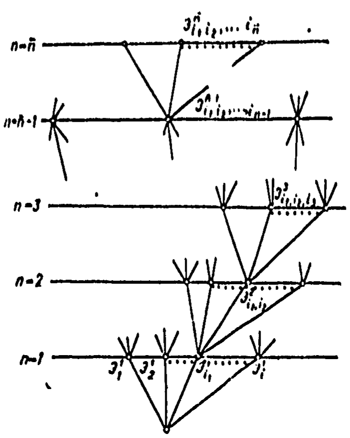

Figure 8.6. Variant Decision Tree

Below we shall dwell on the procedure for resolving the examined task, for which the spatial dimension for the conditions is practically neutral, but is actually a collection of points ΔV which approximate the allowable number U and the number of stages $\bar{n}$. This procedure is known in the schedule theory under the name of the method for the sequential analysis of variants. The process for its realization may be most graphically presented in the form of a variant tree which consists of $\bar{n}+1$ strata (figure 8.6). The zero stratum consists of a single apex called the root of the tree. It corresponds to the initial condition of the system: $Э=Э^0$. The first stratum consists of apexes which correspond to the conditions $Э^1_{i1}=f(Э^0, \Delta V_{i1}, 0)$, where $\{\Delta V_{i1}\}$ is a collection of points which approximate the number U. The apex $Э^0$ is connected by arrows with the apexes $Э^1_{i_1}$. The apex $Э^1_{i}$, $i_1=1, 2,\ldots, \bar{i}$, in turn, generate a group of apexes for the second stratum n=2, which correspond to the conditions

$$Э^2_{i1i2}=f(Э^1_{i},\Delta V_{i2}, 1),$$

where $\{\Delta V_{i2}\}=\{\Delta V_{i1}\}$ and so forth (see figure 8.5).

Each apex is placed in correspondence (aside from the vector of the elements $Э^n_{i_1,i_2,\ldots,i_n}$) to the value of the target function $f^n_{i_1,i_2,\ldots,i_n}$, which correspond to the correction strategy $\Delta V^1_{i_1}, \Delta V^2_{i_2},\ldots, \Delta V^n_{i_n}$, and the remaining "energy" reserve $V^n_{i_1,i_2,\ldots,i_n}=V-\sum_{k=1}^{n} |\Delta V^k_{i_k}|$. Note that in the future we shall consider two apexes as being different if even one of the equations is not fulfilled

$$Э^n_{i'_1 i'_2 \ldots i'_n} = Э^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}, \tag{8.87}$$

$$V^n_{i'_1 i'_2 \ldots i'_n} = V^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}, \tag{8.88}$$

$$f^n_{i'_1 i'_2 \ldots i'_n} = f^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}. \tag{8.89}$$

The case where all of the equations are fulfilled is examined below. On the strength of this condition each apex is connected with the root of the tree only by a single route. If $V^n_{i_1 i_2 \ldots i_n} = 0$, a further construction of the variant is accomplished trivially:

$$\Delta V^n_{i_{n+1}} = \ldots = \Delta V^{\bar{n}}_{i_{\bar{n}}} = 0.$$

In this manner, to each path which connects the tree root with the apex of the n-th stratum there corresponds an acceptable solution. The quantity of apex strata depends on its number. If $i_n \in \{1, 2, \ldots, \bar{i}\}$ when all n, then in the general case the quantity of apexes of the n-th stratum amount to $\bar{i}^n$. This indicates that the construction and retention in EVM memory of the entire variant tree becomes impossible already under small values $\bar{n}$ and $\bar{i}$. Fortunately, the decision procedure to the statement which we have transferred requires a simultaneous retention at each strata of no more than $\bar{i}$, that is altogether no more than $\bar{n} \cdot \bar{i}$ apexes.

The method for the subsequent analysis of the variants comprises three component parts. The first of them determines the technique for a step-by-step construction of the variants which were also presented above. The second defines the number of comparative "conditions," in which the constructed variants are presented. The third formulates the rule of domination for an evaluation of the partial variants which have been constructed at the examined stage.

We shall examine the third part in more detail. Whatsoever pertains to the second we shall consider as two equal conditions if the apexes of a single stratum correspond to them. The first law of domination is corroborated by the fact that the partial variant which generates the apex $Э^n_{i'_1 i'_2 \ldots i'_n}$, dominates the variant $Э^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}$, if three conditions are fulfilled:

$$Э^n_{i'_1 i'_2 \ldots i'_n} \in [Э^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}, \hat{Э}^n] \text{ или } Э^n_{i'_1 i'_2 \ldots i'_n} \in [\hat{Э}^n, Э^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}]; \tag{8.90}$$

$$f^n_{i'_1 i'_2 \ldots i'_n} \leqslant f^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}; \tag{8.91}$$

$$V^n_{i'_1 i'_2 \ldots i'_n} \geqslant V^n_{i^{\bullet}_1 i^{\bullet}_2 \ldots i^{\bullet}_n}. \tag{8.92}$$

The second law is tied in with the construction of an acceptable solution to the problem being examined. From the number of apexes of the first stratum we shall select the apex $\mathcal{E}^1_{i_1}$, which embodies the smallest value $f^1_{i_1}$. To this apex there corresponds a certain subset of apexes of the second stratum from which we shall also select an apex which embodies the target function through the lowest value. Let this apex be represented as $\mathcal{E}^2_{i_1 i_2}$.

Continuing this process, we shall construct a subset of apexes of the n-th stratum. The best of their number will determine a certain acceptable solution which, generally speaking, may not even be optimum. Further, we shall again return to the $(\bar{n}-1)$-th stratum, eliminating the apex $\mathcal{E}^{\bar{n}-1}_{i_1 i_2 \ldots i_{\bar{n}-1}}$ and investigating the remaining similar cases described above. Further, returning to the subset of apexes $\mathcal{E}^{\bar{n}-2}_{i_1 i_2 \ldots i_{\bar{n}-3} i}$, $i = 1, 2, \ldots;\ i \neq i_{\bar{n}-2}$, we select the best apex from those remaining, and again transfer to the $(\bar{n}-1)$-th and the $\bar{n}$-th strata, etc. Each time the best of the selected strategies is retained in the memory, and the number of tree apexes is monotonically reduced.

Thus, let the value for the target function of the best of the derived strategies be f^*_0. Let us examine an arbitrary tree apex $\mathcal{E}^n_{i_1 i_2 \ldots i_n}$. Corresponding to it is a class of possible correction strategies which are characterized on the first n stages by the impulse values $\Delta V^1_{i_1}, \Delta V^2_{i_2}, \ldots, \Delta V^n_{i_n}$ and the target functional values $\sum_{k=0}^{n} f_0(\hat{\mathcal{E}}^k, \bar{\mathcal{E}}^k, k)$. Let us examine for this class the evaluation below (the border) of the optimum target functional value $f^*_{0 i_1 i_2 \ldots i_n}$. It is apparent that

$$f^*_{0 i_1 i_2 \ldots i_n} = \sum_{k=0}^{n} f_0(\hat{\mathcal{E}}^k, \bar{\mathcal{E}}^k, k) + \Delta f^*_{0 i_1 i_2 \ldots i_n},$$

and in the capacity of $\Delta f^*_{0, i_1, i_2, \ldots i_n}$ one may derive the value which corresponds to n+1, n+2, ..., n-th stages and which is received as a result of the step-by-step minimization function $f_0(\hat{\mathcal{E}}^l, \bar{\mathcal{E}}^l, l)$, $l \geqslant n+1$, under the restrictions

$$\mathcal{E}^{l+1} = f(\mathcal{E}^l, \Delta V^l, l), \ \Delta V^l \in U, \qquad (8.93)$$

where as an initial vector value $\mathcal{E}$ the vector $\mathcal{E}^*_{i_1 \ldots i_n}$ is derived.

The second rule of domination, more precisely, the rule for evaluating the hopelessness of a partial solution, corresponds to the apex which consists in checking the inequality of $\mathcal{E}_{i_1 i_2 \ldots i_n}$:

$$f^*_{0 i_1 i_2 \ldots i_n} > f^*_0. \qquad (8.94)$$

If it is fulfilled, then the apex $\mathcal{E}^n_{i_1 i_2 \ldots i_n}$ is eliminated from further examination.

In conclusion we note that the procedure presented for the sequential analysis of variants yields the first acceptable solution saving several seconds of machine time. In the future the solution may be shortened at any moment in time and therefore an approximate solution would be derived at any rate. And it may be optimum, however, the "proof" of this fact requires significant expenditures of time.

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GEOPHYSICS, ASTRONOMY AND SPACE

DISTRIBUTION OF CONTROL BETWEEN GROUND AND SPACEBORNE COMPLEXES

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[Chapter 10 by G. G. Bebenin, B. S. Skrebuchevskiy and G. A. Sokolov from the book "Sistemy Upravleniya Poletom Kosmicheskikh Apparatov" edited by G. G. Bebenin, Mashinostroyeniye]

[Text] Principles of Functional Distribution Between Ground and Onboard Control Complexes

10.1 Principles of Functional Distribution Between Ground and Onboard Control Systems

At the present time a definitive approach to the solution of the problem concerning the rational distribution of functions between ground and onboard control complexes in the KA [spacecraft] flight control process has still not been formulated. This is explained by the great variety of research which is being performed in space and the different "level of responsibility" for the control systems in the execution of the assigned task. Actually, if on automatic KA malfunctions in the flight control system may lead to the failure of certain portions of the experiment, then on piloted KA a malfunction in the control system may represent a serious danger for the life of the crew. A great responsibility in the latter case lies in the system for monitoring the functioning of a complex life support system and the KA as a whole. It is apparent that in order to resolve the problems of controlling piloted spacecraft one must in combination accomplish redundancy with the aid of onboard control systems.

In figures 10.1 and 10.2 functional KA control diagrams are presented. In the first case all the control commands are formulated at the ground control point and are transmitted for action to the KA through an onboard decoding and programming device. In the second case, a schematic is presented of a semi-autonomous KA flight control system. As a rule, in the variant being examined, a BTsVM [onboard digital computer] is included in the onboard control system loop. On the ground are decided the basic, most time-consuming tasks in determining the location of the spacecraft (processing tracking data and predicting orbital elements), processing initial data which is necessary for controlling the angular positions of the equipment, etc. To the onboard control system may be entrusted such tasks as controlling the angular positioning, compressing telemetric data and so forth.

In distributing the functions between the ground and onboard control systems we must also take into account those factors such as the distance of the KA from the earth. A large distance leads to a significant time delay in the control signals. In figure 10.3 there is presented a graph of the time delay of contro signals between a hypothetical KA located in the vicinity of Mars and a ground control point during the period 1975-1976.

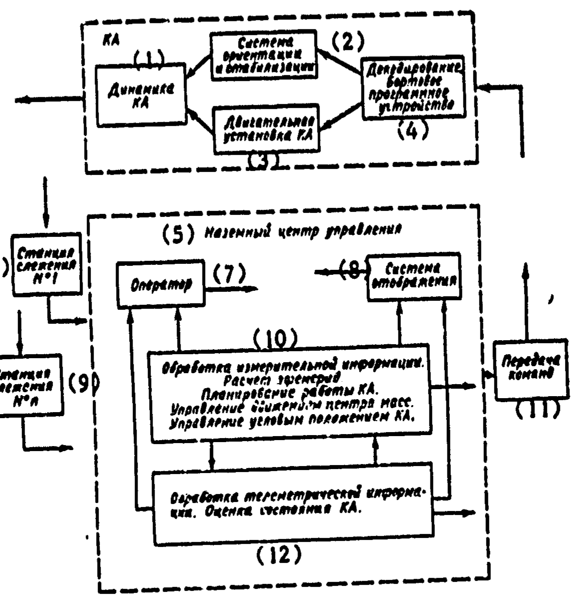

Figure 10.1. Command Control of a KA Flight

Key:
1. KA dynamics
2. Orientation and stabilization system
3. KA engine system
4. Onboard decoding program device
5. Ground control center
6. Tracking station nr. 1
7. Operator
8. Display system
9. Tracking station nr. n
10. Processing measurement data
    Calculating ephemerides
    KA operations planning
    Controlling the motion of center of mass
    Controlling KA angular position
11. Transmission of commands
12. Processing telemetric data
    Evaluating KA status

The average signal time delay for a six-month program of research amounted to approximately 15.2 minutes. The very time for the reception of decisions in especially complex situations may amount to much shorter intervals.

Thus, it becomes apparent that spacecraft intended to investigate the surface of a planet must possess a high degree of autonomy and a high degree of reliability to enable them to analyze the surrounding conditions and control the investigations in response to their changes.

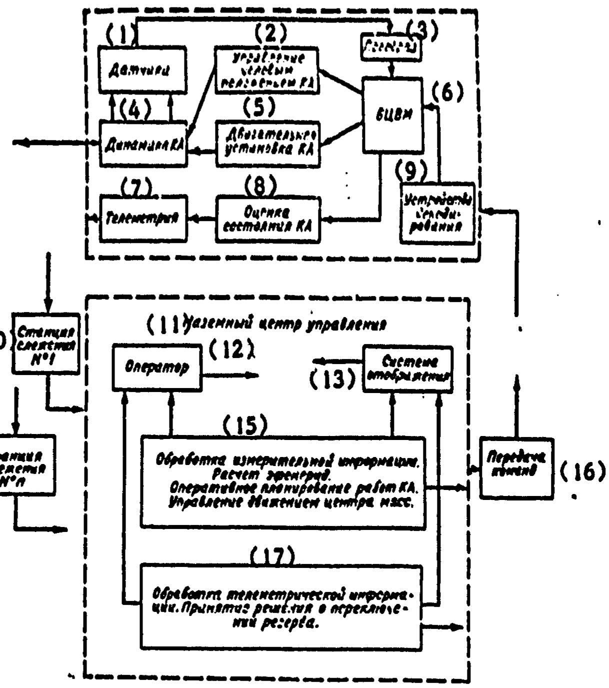

Figure 10.2. Semiautonomous Control of a KA Flight

Key:

1. Sensors
2. Control of KA angular position
3. Tranformation
4. KA dynamics
5. KA engine system
6. BTsVM
7. Telemetry
8. Evaluation of KA status
9. Decoding device
10. Tracking station nr. 1
11. Ground control center
12. Operator
13. Display system
14. Tracking station nr. n
15. Processing measurement data
    Calculating ephemerides
    Operational planning for KA work
    Controlling the motion of center of mass
16. Transmission of commands
17. Processing of telemetric data
    Making decision for switch-over to reserve

In figure 10.4 there is presented a functional block diagram of a spacecraft control system intended for the investigation of planetary surfaces. The basic system for control and monitoring the status of the spacecraft is the BTsVM which facilitates the accomplishment of the following functions:

to perform navigation and calculations for the control of specialized sensors (for example, solar and stellar sensors, antennae, etc.);

estimate the position, determine course and work out the corresponding control commands;

formulate the logic for successive operations which are performed by the attitude control system and synchronization of the operation of the various systems of the spacecraft; and

to evaluate the status of the KA and take measures concerning the use of energy resources.

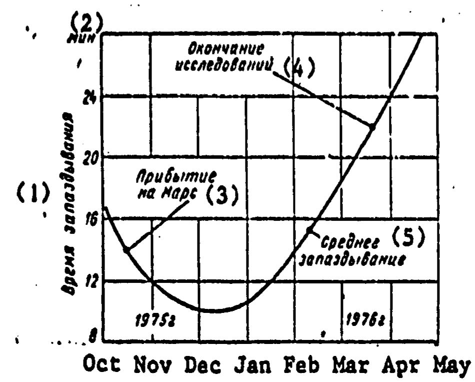

Figure 10.3. Graph of Radio Signal Delay for Communications Between Mars and Earth

Key:

1. Time of delay
2. Minutes
3. Arrival at Mars
4. Termination of research
5. Average delay

It should be especially noted that the capability of a system to detect a malfunction and restore the functioning of the KA under conditions of extended functioning and a great distance from the earth gives great advantages to autonomous control and monitoring systems.

The examples of the control systems being examined allow one to generalize, if only approximately, an approach to the rational distribution of control functions between ground and onboard control systems. Assume that for control of a KA it is necessary to fulfill m_Σ operations (the measurement, processing of measurements, forecasting the formation of control signals and so forth). From these n_k may be realized by autonomous systems on board the KA, l_H is only with the assistance of a ground control point and $k_{\text{нп}}=m_\Sigma-(n_k+l_н)$ may be similarly successfully realized both onboard the KA and on the ground. The solution concerning the distribution of

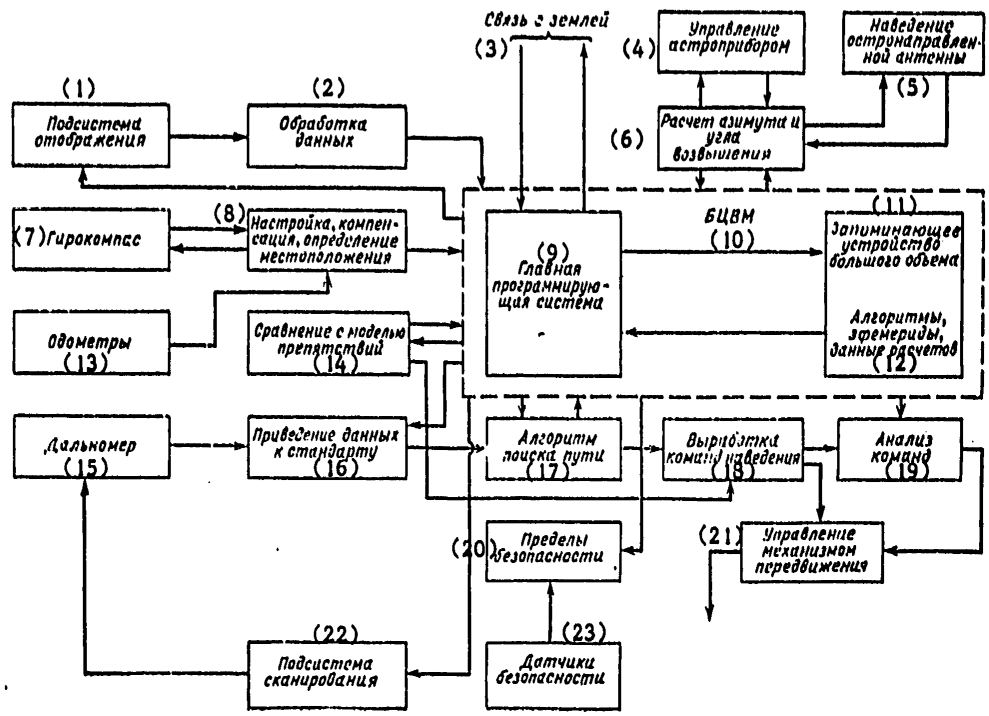

Figure 10.4. Functional Diagram of an Onboard Control System for an Apparatus Moving About the Surface of a Planet

Key:

1. Display subsystem
2. Data processing
3. Communications with Earth
4. Astroinstrumentation control
5. Pointing of astro-directed antenna
6. Calculation of azimuth and elevation angle
7. Gyrocompass
8. Tuning, compensation and positional determination
9. Primary programming system
10. BTsVM
11. Large capacity memory device
12. Algorithms, ephemerides and data calculations
13. Distance gages
14. Comparison with obstacle model
15. Rangefinder
16. Reducing data to a standard
17. Route searching algorithm
18. Processing of guidance commands
19. Command analysis
20. Safety limits
21. Control of the mechanism for motion
22. Scanning subsystem
23. Safety sensors

control functions may be derived through calculating the general evaluation criteria for the efficiency of the control system as a whole. Depending on the purpose of the KA and the work being performed or the investigations these criteria may be various. They may be, for example, the cost of the complex's operations (Q_y), or the reliability of their performance (P_y). In this and other conditions the selected criteria depend on the distribution variants for the control functions, that is

$$Q_y = \Phi_y(m_\Sigma, n_к, l_н, k_{кн}); \quad P_y = \Phi'_y(m_\Sigma, n_к, l_н, k_{кн}). \qquad (10.1)$$

Performing the analysis for the various control system structures, one may derive the characteristics the approximate form of which is presented in figures 10.5 and 10.6. From these it follows, for example, that if as a criterion one is to select the cost for creating a control system, then one may select variants close to W_{a_0}, which provide the lowest expenditures for the creation of a KA control system and which allow for the performance of the flight's objectives. One may pursue similar reasoning in the case of selecting the other criteria.

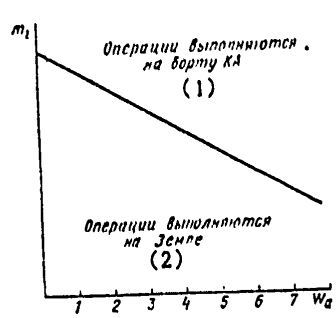

Figure 10.5. Distribution Graph for Control Operations Between Onboard and Ground Complexes

Key:
1. Operations performed onboard the KA
2. Operations performed on Earth

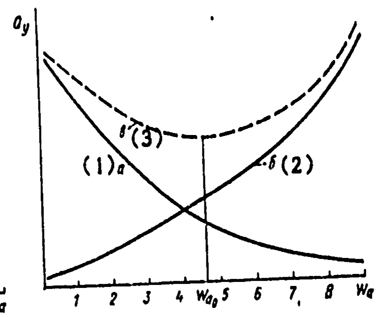

Figure 10.6. Cost Graphs for Control Systems

Key:
1. Cost of onboard control system
2. Cost of control from Earth
3. Total cost

10.2 General Principles in the Rational Distribution of Crew Functions and Automatic Devices in Onboard Control Complexes of Manned KA

In the development of the control systems of manned KA there exist two conflicting tendencies. This is, on the one hand, a quest to relieve the crew as much as possible and charge as much as possible the control functions to automatic devices, and on the other hand the quest to utilize to a maximum the capabilities of man to increase the efficiciency in resolving control problems.

The relationship between these tendencies is constantly changing both as a consequence of the development and improvement of technology as well as the development and improvement of the capabilities of man.

An important consideration in this case also exists in the level of scientific knowledge concerning the capabilities of man and concerning the principles of interaction between his individual organs and the organism of the systems in the control process. Consequently, the solution concerning the distribution of functions for the crew and automatic devices should be taken as a specific control task taking into account the conditions designated above during the design period for a KA control system. However, the capability exists to formulate general principles for resolving the given task.

To accomplish this we shall propose tasks which are being performed by individual functional systems of onboard control complexes such as complex systems in the form of multi-level structures (10.7). In this case, there are introduced three levels which we shall call executive, command-signal and directive.

The lower, executive level, provides for the creation of necessary control forces and moments to control maneuvering, as well as orientation and stabilization of the KA in conformance with the command signals and the returned communications signals concerning the current motion parameters of its center of mass and the motion about its center of mass. Consequently, it includes n control loops which process the displacement error between the required values of control parameters (command signals) and their current measured values.

Next, the command-signal level is intended to process the control signals (designated above the displacement errors) for the executive level. These signals are output by a information processing system (BTsVM). In addition, At the given level the BTsVM is represented by a system for formulating the control laws, a system for formulating command signals and a system for monitoring the functioning (efficiency) of the onboard systems and the KA status. The system for processing data and measuring the devices jointly with the executive level form n closed loop controls of the servo system type.

Control of the operations which are performed at the command-signal level is conducted by the signals proceeding from the higher directive level in accordance with the afferent signals concerning the status of the control process and the control system. At the directive level the decision is recieved concerning the necessity to fulfill at a given moment any type of control operation concerning the capability or method for control in accordance with the flight program and the actual situation, as well as perform the selection of the control loops and rules. All this may be performed both with the aid of BTsVM and at the ground control point.

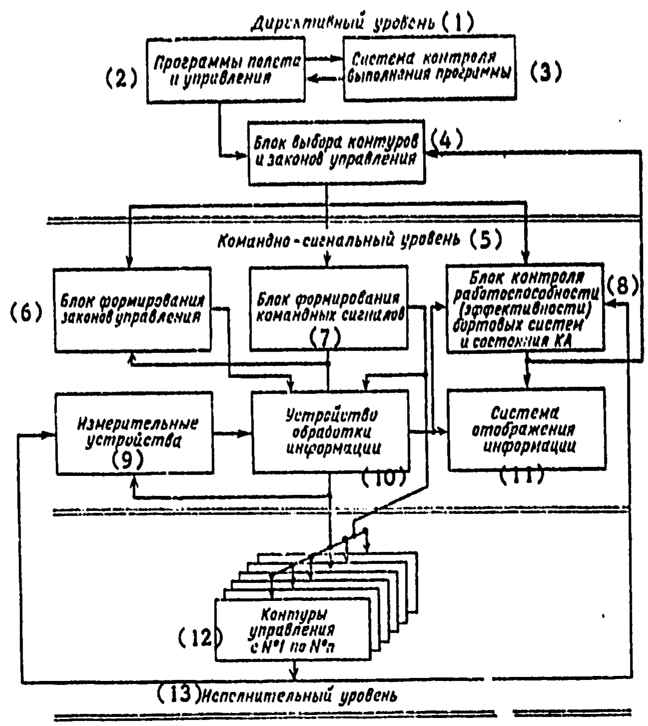

Figure 10.7. Hierarchical Structure of an Onboard Control Complex

Key:

1. Directive level
2. Flight and control programs
3. System for monitoring program execution
4. Assembly for selection of control loops and laws
5. Command-signal level
6. Assembly for formation of control laws
7. Assembly for formation of command signals
8. Assembly for monitoring work capacity (efficiency) of onboard systems and KA status
9. Measuring devices
10. Data processing device
11. Data display system
12. Control loops from Nr. 1 through Nr. n
13. Executive level

For example, according to the flight program it is necessary to perform an approach maneuver with a space object. Taking into account the complexity of the situation, the capabilities of the control system and the capabilities of the crew the decision is made concerning the selection of the approach method, the utilization of the main or reserve automatic control procedure, or concerning the utilization of the manual control system. Information concerning the acceptance of the decision is output to the corresponding systems of the command-signal level.

In this manner, the output signal of the upper level of the hierarchical structure contains information of the directive characteristic which determines the general control strategy. The output signal itself of the next lower level includes specific information for any type of control loop for the executive level, for example, the activation of the control engines for a 90° pitch maneuver or for the creation of thrusting along the longitudinal axis to brake the KA (when approaching the space object), etc.

For the manifestation of the general principles of the rational distribution of functions between automatic devices and crews in controlling a KA in accordance with today's level of knowledge in the area of the anthropological sciences we shall describe the basic systems of the human organism which participate in control in the form of an analogous hierarchical structure (figure 10.8). The highest division of the central nervous sytem (TsNS) is located at the directive level; on the command-signal level is its lowest division and the sensor system, but the motor system is at the executive level. The afferent reverse communications signals are shown in figure 10.8 alongside the control signals by the bow-shaped arrows.

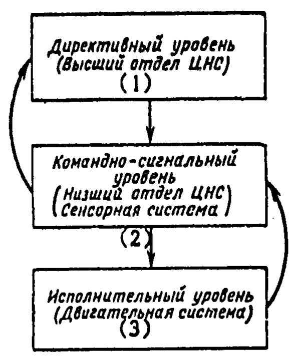

Figure 10.8. Operator Structure as an Element in the Control Loop

Key:
1. Directive level (highest TsNS division)
2. Command-signal level (Lowest TsNS division -- sensor system)
3. Executive level (engine system)

A similar presentation is based on the fact that at least at the present time and in the near future any kind of participation by man in the control system is connected with a motor action by him, and within the physiology of motion in every motor action there are distinguished his purposeful structure; and his motor formation.

His purposeful structure flows from the nature of the originating motor task and determines the guiding level (control loop) which is in a position to fulfill the task. His motor formation is determined not only by the task. It also depends on the motor capabilities of man for a given task, the arrangement of his kinematic bonds, the presence of some type of equipment, the maintenance of accumulated experience, etc.

Their extensive internal coherence is a characteristic feature of experienced, well worked out, movements. The adapted changeability of experience movements grows steadily with the increase in the sensed complexity of the movements. In this case, the role of the highest level of TsNS increases; that is of the higher level of the indicated hierarchical structure.

In addition, the psycho-physiological investigations of man's motor activity show that the highest section of TsNS does not command in detail the entire process of movement. It, similar to the directive level of a hierarchical structure in figure 10.7, determines the control strategy for this movement, that is it accomplished the designation of a determined mode in the widest sense of this terminology, monitoring and the switchover and its adaptation to the indicated characteristics of the situation and the task being solved.

The lowest section of TsNS controls man's motor system with relative independence based on information from the sensor system. The higher the level of its independence, the lesser the perceived complexity of the action. As a result of the interaction of the lower TsNS section, the sensory and motor systems at the two lowest levels of the hierarchical structure (see figure 10.8) through the fulfillment of separate motor acts closed control loops of their own type which function independently from the highest section of TsNS. They are to a significant degree analogous to the closed control loops mentioned above at the two lowest levels of the hierarchical structure (see figure 10.7).

The degree of independence for the closed loops of man's organism under other equal conditions (an identical degree for the perceived complexity of an action) grows with respect to training. With a significant change in a situation the lowest section delivers according to a rising afferent line of its own type a warning signal concerning the impossibility of solving the task within the bounds available to it for the variations of action. In accordance with this signal the highest TsNS section significantly reprograms the entire strategy for accomplishing the action.

In this manner, here also are examined the designated functional analogy of the hierarchical structures (see figures 10.7 and 10.8). Actually, in accordance with the information concerning the working capacity (efficiency) of the onboard systems and the state of the KA the directive level (see figure 10.7) also accomplishes a change in the control strategy. However, taking into account the fact that the highest TsNS level of man significantly exceeds in its capabilities any computer, the directive level of the structure in figure 10.8 features a significantly finer internal organization which for several tasks, for example, the acceptance of heuristic decisions, the evaluation of obstacles, etc., is simply not attainable at a corresponding level of the first structure.

In addition, the independent control loops which are being formed at the two lowest levels of the second structure according to a number of indicators (time delay, precision in the fulfillment of control operations, etc.) may yield to analogous loops of an automatic system. In addition, the execution by man of similar operations over a long period of time results in fatigue and a dulling of consciousness, as a result of which the activity of the highest section of TsNS is lowered.

Based on this comparative analysis which has been presented for two hierarchical structures one may formulate the general principles for the rational distribution of the functions of a crew and automatic devices for the onboard control complexes of manned KA.

First Principle. The highest degree of crew participation (in priority) is envisaged at the highest level of the hierarchical structure for the onboard control complex. The technical devices which support the work of the crew should be planned in such a manner that they concentrate the main amount of work for the highest TsNS section of the crew members and to a maximum degree simplify the work of the lowest section.

Second Principle. Crew participation in controlling the signal-command level according to the basic variant (under nominal conditions) is expediently limited by the operations which are required for the uninterrupted or frequent attraction of the highest TsNS level, as well as by the operations concerning which the most precise and complete information may be derived only directly from the sensor system of man. Under the remaining conditions, according to the basic variant, the automatic control system is used.

Third Principle. For operations which in the basic variant are accomplished with the use of an automatic control system, it is expedient to provide for a reserve variant using a manual control system. In this case, there should be provided an organic combination of systems for automatic and manual control under which is understood:

the unity of logic for automatic and manual control systems; and

the capability for a smooth transition from the automatic mode to the manual control mode and back again.

Fourth Principle. Regardless of the degree of crew participation in the control system the information displays should provide a sufficiently complete presentation by the crew concerning the character of the control process at all stages of flight at the formation of its model at the higher TsNS section.

We shall note the particulars in realizing these basic principles.

The first principle is primarily concerned with the sphere of interaction by the crew with the BTsVM. This means primarily that the data concerning the operation of the BTsVM which has been output to the crew should be, on the one hand, sufficiently complete and, on the other hand, its presentation format should be the most convenient for perception. To simplify the operation of the lower TsNS section alongside with the optimization of the data presentation format may also be at the expense of selecting the convenient control organs and data input devices by the crew into the BTsVM. It is also necessary to preclude possible errors by the crew in the operation of the BTsVM. All of this requires a careful processing of the programs and the large volume of experimental research.

The calculation of the second condition may serve as an example for the control of space objects as they approach over small distances (mooring). In this case, the cosmonaut with the aid of optical devices can better determine the angular velocity of the line of sight against the interference background, the resultant vibrations of the KA shell about its center of mass, as well as the approach velocity, than with technical devices. Therefore, as experience has shown in the flights of manned KA in our country and in the U.S., the approach at this stage is performed better qualitatively with the use of a manual control system.

Over distances which exceed the mooring range in the nominal approach variant the manual control system does not have special advantages, since it does not require the attraction of the highest TsNS section of the cosmonaut. With sufficient training the participation of the cosmonaut in control will be completed at the lower levels of the hierarchical structure. Therefore, for the basic variant the automatic control mode is usually accepted. In the interests of increasing efficiency and solving a problem in the capacity of a reserve a manual control mode is envisaged (third principle), and presented to the crew is the complete information concerning the parameters of relative motion (fourth principle).

The last guarantees the uninterrupted participation of the crew in the control process. In this nominal variant he works in the informational mode, that is he accepts the data concerning the control process and monitors the operation of the automatic systems, that is the highest TsNS section is utilizied and the lower levels of the hierarchical structure (in figure 10.8 the first principle is realized) are removed.

During a deviation from the nominal mode (for example, during a failure of the automatic control system) the crew transfers to the active mode and directly performs the approach with the aid of the manual control system. Continuity here is understood in the sense that the crew within the transfer process has a detailed presentation concerning the control process.

To increase the efficiency of the transfer from the automatic mode to the manual control mode it is necessary to ensure unity in the algorithms or laws (unity of logic) for control, which are being realized within the automatic and manual control systems. It is natural that within the manual control mode it is not always possible in a pure sense to realize an algorithm (or law) of control which is being used in the automatic mode, since the latter may be tied in with rather complex computer operations. In this case, kept in view is the utilization for the manual control of a simplified algorithm (law) which stores, however, the primary characteristics of the precise algorithm.

The given requirement is necessary, but is not a sufficient condition for the organic union of the automatic and manual control systems.

An adequate condition for the organic union of the automatic and manual control systems is the capability for a smooth transition from one mode to the other, under which is understood the active inclusion of the crew in the control process at any moment without any kind of rearrangement within the system and accomplishment of the supplementary operations. The following procedure for the control process should be its natural continuation at the previous level.

In order to satisfy this condition, in certain cases there is a sense of rejecting the traditional, well-studied control methods, because they, even sometimes giving a good result in an automatic control mode, do not allow one to receive a high degree of efficiency in solving the task on the whole.

10.3 Autonomous Control Systems

The concept of autonomy in this case is examined from the position of cooperation between the ground and onboard complex. Consequently, understood under contro autonomy is the independent functioning of the onboard control complex without any kind of communications with the ground complex. This includes independent processing of commands, as well as the reception of all necessary flight navigational data on board the KA. Let us examine the basic principles for the construction of automatic control systems in a number of characteristic examples:

the rendezvous of a transport ship with an orbital station;
orientation and guidance in the orbital correction of a KA; and
orientation and mavigation in the fulfillment of scientific experiments.

A rendezvous operation consists of the following stages: search for the space object with which the rendezvous is to be accomplished; approaching the object to be met; and mooring.

Search is performed either with the use of radiotechnical devices which rotate their field of illumination, or with the use of optical devices. In the latter case the KA rotates with the aid of the manual orientation control system until detection and "lock-on" of the object. Following this the approach stage begins. The primary difficulty in solving this problem is in the limited energy capacity of the KA.

In the approach problem for a KA having a single engine system, utilization of the classical guidance methods, and in particular, the method for the parallel approach for correcting parameters of relative motion, does not permit the realization of this principle totally, since the crew does not have the capability to maintain constant visual contact with the object being approached. Moreover, even in the automatic mode the quest to apply the parallel approach method for the KA with a single engine system leads to a number of deficiencies. In this case a successive dampening of the angular velocity along the line of sight (error correction) is actually produced and maintenance of approach velocity is within the assigned limits (acceleration or braking) which requires periodic rotations of the spacecraft about the pitch axis within the guidance plane at angles of 90° and 180°. The existance of an area of uncertainty within the measurement of angular velocity along the line of sight which is the result of self-induced oscillations within the orientation system leads to overcorrections in the lateral channel (figure 10.9a) and excessive expenditures of fuel.

The noted deficiencies are absent in the case when a method of parallel approach is realized through coordinated control, that is when the KA has engines creating some kind of thrust level along three axes which are connected wtih a system of coordinates. This type of engine arrangement scheme has been justified for small corrections. In particular, it is advisable to use it during the final stage of approach and mooring, and for the precision control of the parameters of relative motion. For entrance of the KA into the mooring zone it is more rational to apply one or two engine systems of comparatively great thrust.

It is advisable to distribute these engine systems in such a manner that they will create a thrust vector perpendicular to the x axis (figure 10.9b), a sector for visual observation (for the optical axis of the measurement instruments) and guidance to be accomplished through the method of guaranteed flight, the essence of which consists of the following. The KA is constantly oriented at the x axis along the line of sight in the direction of the object being approached (the target). The y axis coincides with the guidance plane. Correction of angular velocity along the line of sight (lateral velocity V_6) is accomplished by activating the engine system. For every i-th correction the lateral velocity is diminished to the value

$$V_{6i} = \omega_1 \rho_i, \tag{10.2}$$

where ω_1 is the remaining angular velocity along the line of sight; ρ_i is the distance to the object being approached at the moment of the i-th correction which guarantees a constant direction of the target object and exit to the determined distance ρ_{Ti} from the target on the traverse. As a result of each subsequent correction, the distance on the traverse is reduced, and ultimately the KA is guided into the mooring zone.

A significant characteristic of such a guidance method consists of the fact that as the approach is made to the traverse the approach velocity decreases to zero without correction in the direction of the line of sight. This indicates that through the creation of thrust along the y axis control is guaranteed in both the lateral and the longitudinal regimes. Following the exit of the KA into the mooring zone one may transfer to coordinated control through the use of low-thrust engines.

With the objective of conserving time and fuel expenditures at the mooring stage it is advisable to have the lowest possible ρ_T value at the moment of the final correction. This may be achieved through a reduction of ω_1 in the expression (10.2). However, the possibilities for its reduction, as were noted above, are limited by the zone of uncertainty in measuring the angular velocity along the line of sight, which is determined by the maximum angular velocity of the KA's self-induced oscillations about its center of mass and by errors in the measuring complex.

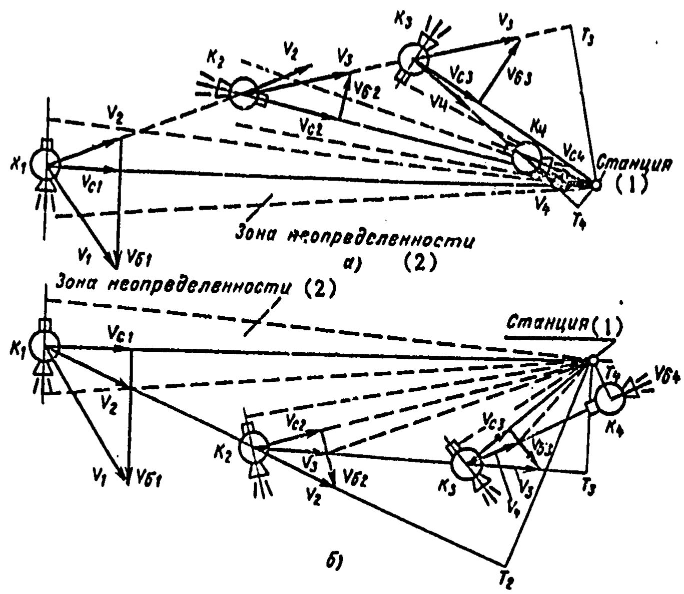

Figure 10.9. Approach Schematics: a) By the Parallel Approach Method; and b) By the Method of Guaranteed Flight

Key:
1. Space station
2. Zone of uncertainty

Important for this guidance method is also the question concerning the selection of the angular velocity along the line of sight ω_2 at which activation of the correction engine is performed. Analysis has shown that the expenditure for a characteristic velocity grows with an increase of ω_2. Therefore, from the point of view of economy it is advisable to take the smallest possible ω_2 value. However, in so doing the required number of corrections grows sharply. Consequently, in the absence of limitations on the number of engine activations in the capacity of ω_2 for an automatic control system it is advisable to accept its minimum value which is determined by a hysteresis of a relay amplifier through a voltage dropout corresponding to ω_1. And in a manual control system ω_2 should be located on the border of positive discrimination by the crew for the values ω_2 and ω_1. Given the indicated limitation of ω_2 it follows that one should select from the condition provision of an acceptable number of correction engine activations.

To resolve the problems of autonomous orientation, guidance and navigation inertial systems and devices for astronomical measurements are used. The last may be applied both independently during the orientation of the KA relative to the stars during the performance of astronomical experiments, as well as jointly with the inertial system. We shall examine the principle of constructing such a combined system using as an example the astroinertial system of the "Apollo" KA which includes an assembly of inertial measuring and optical astromeasuring instruments.

The inertial measurement assembly is designed to determine the orientation of the KA in inertial space. It is based on a gyrostabilized platform in a three-function Cardan suspension. Three two-function integrating gyroscopes are installed on it. The signals from these gyroscopes which arise through the action of perturbation on the platform are fed to the momentum motors which create compensating perturbations of the platform. To measure the acceleration of the KA under the influence of reactive thrust and aerodynamic forces on the platform three accelerometers with mutually perpendicular axes are installed. Prior to launch the gyro platform is calibrated to an accuracy of 1" [5].

The inertial assembly is in the shape of a sphere with a diameter of 320 mm and a mass of 19.3 kg. It requires an electrical power of 217 watts with a voltage of 28. The platform with a mass of 17.9 kg has an overall size of 686 x 559 x 114 mm. Integrating gyroscopes with a diameter of 63.5 mm are placed in a helium atmosphere to insure the designed temperature regime. The integrating accelerometers use as sensory elements metallic floats 40.6 mm in length. They are also located in a helium atmosphere.

The gyroscopes and accelerometers employed in these systems feature much greater accuracy than is required to resolve the tasks of the "Apollo" KA. This circumstance allows one to predict the failure of the system based on periodic checks of measurement accuracy through the indicated elements. Gyroscope errors are determined through astronomical measurements which are performed to periodically correct the gyro platform. The accuracy in measuring the accelerometers is evaluated through their null displacement (the output signal under zero acceleration) during the process of passive flight. A decrease in accuracy is a sign of a possible future system failure.

Error measurements are also used to improve the overall accuracy of the inertial measurements. Their processing by an onboard computer allows one to determine gyroscopic drift, the mathematical expectation for accelerometer null displacement and inputting the appropriate compensating signals.

The results obtained during the flight of the "Apollo-8" KA show that the null displacement of the accelerometers did not exceed 0.1 cm/sec^2, and the root-mean-square values for gyroscopic drift along the three axes of the KA amounted to 41", 31" and 58" over a period of 10 revolutions [5].

With the objective of increasing the reliability in the lunar model an auxiliary non-platforming inertial system consisting of three rate gyroscopes and three integrating accelerometers was installed, as well as a special computer. It was used as an emergency control system.

The gyroscopes have a measurement range of 25 deg/sec with a discrete digital data output of 3.15 arc sec/impulse. The measurement range of the accelerometers amounts to 3 g with a discrete digital output of 0.0009 m/sec^2/impulse. The sensors are rigidly attached to a precisely installed framework aligned relative to the axes of the KA.

The optical measuring system includes a sextant and a wide-angle scanning telescope. Only the telescope is included in the onboard complex of the lunar model. The mountings on which the optical instruments are installed are stabilized by a gyro platform of a corresponding system.

The wide-angle scanning telescope has a 60^0 angular field of view under a single magnification factor.

The sextant has two viewing paths with a field of view of 1.8^0 with a 28-position imaging magnification.

The sextant is used for navigational measurements: determining the angle between the direction towards a star and the horizon (earth or moon) or the angle between the direction towards a star and towards a known orientation on the surface of the earth or the moon. The angle is measured by combining the images (of the horizon and the star or the orientation and the star) by turning the viewing plane (of the optical system) and the movable path (rotating the directed mirror). In so doing the central lines of the paths' fields of view are combined with the directions towards the viewed objects, and the corresponding sensors read off the desired angles.

The telescope of the lunar model is designed for the correction of the gyro platform through measurement of direction towards the star. It has a field of view of 60^0 with a 9-power magnification.

10.4 Semiautonomous Control Systems

The creation of a totally autonomous onboard control complex represents an exceptionally complex task. Moreover, such a solution is scarcely warranted since it leads to excessive complexity in the onboard complex, and consequently to an increase of its mass and a decrease in reliability. Therefore, in practice semiautonomous control systems have received broad application.

Known semiautonomous systems are constructed on the following principles:

the ground complex generates the look angles and determines the general control strategy, and the entire subsequent control process is accomplished autonomously;

control is totally accomplished by the ground complex, and the autonomous systems of the onboard complex are reserves; and

control is accomplished through the assistance of autonomous systems, and the ground complex is used for their periodic correction.

As examples for the realization for the first principle one may offer the control systems for rendezvousing with space objects and their astroorientation system. Within these control complexes the ground complex outputs the command (updates) for the KA rotations, which insure target lock-on (the object being approached or a star) by the onboard measurement devices. Following target lock-on the control process is accomplished autonomously.

The "Apollo" KA control system may serve as an example for the realization of the second principle. Within this system all measurements and processing of command signals are performed by the ground complex. However, on board the KA parallel autonomous navigation measurements are being performed with the aid of the astroinertial system described above. The results of these measurements permitted the monitoring of the operation of the ground complex (the accuracy of the processed commands being submitted to them) and in case of the unexpected provided the capability to transfer to the autonomous control mode.

The third principle is more completely realized in the process of controlling a KA deorbit to the surface of the earth. During this stage the ground complex may be utilized only at the very beginning of the control process for correcting the entry trajectory into the atmosphere and for information concerning the inertial system which is subsequently used for autonomous control of the KA's descent. This correction should create the necessary conditions for getting the returning spacecraft into the atmospheric entry corridor which is determined by the following limitations.

If entry into the atmosphere occurs at a very small angle, then the spacecraft quickly skips off the upper atmospheric layers and flies off at a great velocity. In this case the length of the reentry trajectory and the flight time are sharply increased (the repeated entry is performed in the very same region as the orbital period). However, under a very steep entry the crew will experience heave G-loading and the spacecraft will be subjected to severe aerodynamic heating. Therefore, the entry corridor is restricted by a predetermined range of entry angles depending on the magnitude of the entry velocity.

The indicated corrections in the basic variant are performed according to data from the ground command-computing complex which outputs the necessary updates through telemetric channels in the form of a required thrust impulse value and its orientation. The onboard control system processes these updates -- accomplishes the orientation with the aid of the data from the inertial measuring system and switches on the engine. Activation of the engine is performed upon command by the computer when the signal concerning the impulse value as measured by the integrating accelerometer does not equal the required value.

With the objective of improving the reliability of the correction a capability for its autonomous fulfillment is usually provided for. In this case the required impulse value and its orientation are determined by the BTsVM according to data from the navigational measurements which are performed by the crew. The most precise onboard navigational measurements may be performed with the aid of the sextant. In this case the angle is measured between the direction towards a star and the direction of the earth's horizon, that is the astronomical altitude of a heavenly body.

To improve the reliability of the correction it is useful to provide for a check of the accuracy of the navigational stars selected by the cosmonaut. This task may be resolved by a preliminary directing of the sextant's field of view towards the selected star, taking into account that is seemed to be the brightest of all the stars located within the field of view. In addition, one may utilize the measurements of the angle between the selected star and another known star with its subsequent correlation to the corresponding value in the catalog.

The results of the navigational measurements are used in the calculator to determine the corrections for a predicted parameter (in this case the entry angle into the atmosphere) in order that based on a comparison of the forecast data and the calculated parameter value the updates are determined for the correction.

Following entry into the atmosphere, control of the descent is usually provided by an automatic system. To improve the reliability of control during this stage reserve systems are also provided for. The utilization of a manual control system is proposed as a reserve system. We shall examine the possible principles for constructing automatic and manual control systems for the descent based on the example of the "Apollo" reentry craft.

Immediately prior to entry the control system orients the spacecraft so that following entry a lifting force will be created which is directed downward til that time when the spacecraft is captured by the atmosphere. Under large entry angles the orientation system provides for direction of the lifting force upwards. The initial orientation of the lifting force is kept until a determined G-loading n_p is attained following which the flight begins with a constant loading until a given descent velocity value V_{cH}. For the "Apollo" return spacecraft n_p=1.4 and V_{cH}=210 m/sec.

Following this, the control system switches over to a prediction control mode. Initially, the velocity value at perigee and the current angular distance to perigee are predicted, and depending on their values a lifting orientation vector is performed. Then a prediction of the velocity and inclination angle of the trajectory at the point of ricochet is performed.

If this velocity is greater than orbital, then a flight segment with constant drag is input.

Simultaneously the distance is calculated for the ricochet segment and the distance of the second plunge into the atmophere. These data are compared with the distance to the calculated landing point (target). If the predicted distance exceeds the distance to the target, then the flight mode with constant drag is again input. The prediction is repeated every two seconds until the predicted distance is not less than the distance to the target. If the predicted distance is less than the distance to the target by a value greater than 46 km, then a lifting force is created which is directed upwards to a congruence of these distances.

On the ricochet segment the criteria for the beginning and completion for which the condition is $n<0.2$, control of the trajectory is not performed because of the small aerodynamic forces. Under G-loadings of $n<0.05$ stabilization of the returning spacecraft is accomplished along all three axes. Note that if the predicted velocity of the ricochet is less than 5.5 km/sec, then the ricochet segment is accomplished and a second entry begins immediately upon completion of the previous segment of the so-called alignment segment.

During the second entry control is also accomplished through forecasting, but in so doing linear corrections to the reference trajectory are utilized. In the control algorithm a limitation is provided for in the G-loading. If $n>10$, then control of the angle is blocked and the vector of the lifting force is directed upward.

Control of the lateral distance (inclination of the reentry trajectory plane from the target) is performed as a bank. The value of the bank angle is determined by the conditions by controlling longitudinal motion. The sign of the bank is determined by the sign of the predicted lateral distance.

The utilization of two manual control systems is provided for in the reserve systems. The basic element of one of these is the display panel on which the instruments for monitoring the descent trajectory are installed [3,5].

With the failure of the primary and the instrument for monitoring the reentry trajectory control of the descent is performed with the aid of the simplest manual control system. Readings from the accelerometer and the reserve indicator for the bank angle are used as data sources in this system. Thus, flight along the trajectory with quasi-constant G-loading is insured.

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PUBLICATIONS

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Leningrad ISSLEDOVANIYE OKEANA IZ KOSMOSA in Russian 1978

[Table of contents from book by B. V. Novogrodskiy, Gidrometeoizdat]

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CSO: 8144/1333

PUBLICATIONS

INFRARED TECHNOLOGY AND OUTER SPACE

Moscow INFRAKRASNAYA TEKHNIKA I KOSMOS in Russian 1978 signed to press 4 Jul 78

[Table of contents from book by Yu. P. Safronov and Yu. G. Andrianov, 5,150 copies, 248 pp]

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8480
CSO: 8144/1330

PUBLICATIONS

UDC 629.13.02.62-52.001.2

THEORY OF AUTOMATIC CONTROL OF ROCKET ENGINES

Moscow TEORIYA AVTOMATICHESKOGO UPRAVLENIYA RAKETNYMI DVIGATELYAMI (Theory of Automatic Control of Rocket Engines) in Russian 1978 signed to press 25 Nov 78 p 287

[Annotation and table of contents from the book by Aleksey Andreyevich Shevyakov, Viktor Martynovich Kalkin, Natal'ya Viktorovna Naumenkova, Viktor Vasil'yevich Dyatlov. Mashinostroyeniye, 2550 copies, 288 pages]

[Text] This book generalizes the theoretical work in the field of control and governing of liquid-propellant rocket engines (LPRE). A method of mathematical modelling of the complete cycle of operating regimes is given. Elements of the the theory and calculation of the main types of governors used on LPRE and results of studies of their characteristics are given. The book is intended for scientific workers studying control and governing of the engines of aircraft. It may also be useful for teachers, post-graduate students and students in higher educational institutions.

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PUBLICATIONS

UDC 629.7.001.2

DESIGNING PILOTLESS AIRCRAFT

Moscow PROYEKTIROVANIYE BESPILOTNYKH LETATEL'NYKH APPARATOV (Designing Pilotless Aircraft) in Russian 1978 signed to press 29 Sep 78 p 263-264

[Annotation and table of contents from the book by Dmitriy Nikolayevich Shcheverov, Mashinostroyeniye, 3700 copies, 264 pages, illustrations]

[Text] This book is devoted to the optimal design, mainly by computer, of aircraft (AC) and a complex of AC, considered as a subsystem of a complicated technical system (TS). The basics of the theory of technical systems are presented. Questions of the formation of weight, economic and ballistic models and selection of control parameters are considered.

The book is intended for engineers and scientists of design bureaus.

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PUBLICATIONS

UDC 629.78.015:523.42

MECHANICS OF FLIGHT IN THE VENUSIAN ATMOSPHERE

Moscow MEKHANIKA POLYETA V ATMOSFERE VENERY (Mechanics of Flight in the Venusian Atmosphere) in Russian 1978 signed to press 10 Nov 78 p 0002, 230-232

[Annotation and table of contents from the book by Grigoriy Makarovich Moskalenko, Mashinostroyeniye, 900 copies, 232 pages, illustrations]

[Text] This book is dedicated to the problem of flight in the Venusian atmosphere. It substantiates the technical possibility of making Venusian aircraft, making use of the principles of design of aeronautic, aviation and deep water techniques. Methods of calculating the basic characteristics of aircraft are developed, taking into account the aerostatic force. It is shown that penetration of the atmosphere of the planet and to its surface is advisable for the purpose of conducting broad scientific studies.

The book is intended for engineers and scientists studying the design of space apparatus. It may also be useful for students of the corresponding educational institutions.

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